



# LOW HEAT TRANSFER OXIDIZER HEAT EXCHANGER DESIGN AND ANALYSIS REPORT FINAL

CONTRACT NAS3-24238

Prepared for  
National Aeronautics and Space Administration  
Lewis Research Center  
21000 Brookpark Road, Cleveland, OH 44135

Prepared by  
Pratt & Whitney  
Government Products Division  
P.O. Box 109600, West Palm Beach, FL 33410-9600





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**UNITED  
TECHNOLOGIES  
PRATT & WHITNEY**

## **FOREWORD**

This report summarizes the design and analysis of the United Aircraft Products (UAP) low heat transfer oxidizer heat exchanger concept for the RL10-IIB rocket engine and is submitted in compliance with the requirements of NASA Lewis Research Center Contract NAS3-24238.

The preliminary design effort was begun approximately 15 January 1985 by United Aircraft Products in response to an RFQ for a heat exchanger defined by Pratt & Whitney (P&W) Preliminary Purchase Performance Specification (PPS) F-654. The actual design and analysis work was performed by UAP under Purchase Order No. 274771 from P&W and units are being procured under Purchase Order No. 270902. The effort was headed by Thomas D. Kmiec, Assistant Project Engineer.

The following individuals have made significant contributions to the preparation of this report: Paul G. Kanic, Thomas D. Kmiec, and Richard J. Peckham.

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## **SECTION I**

### **INTRODUCTION**

#### **A. BACKGROUND**

The RL10-IIB engine, a derivative of the RL10, is capable of multi-mode thrust operation. This engine operates at two low thrust levels: tank head idle (THI), which is approximately 1 to 2 percent of full thrust, and pumped idle (PI), which is 10 percent of full thrust. Operation at tank head idle provides vehicle propellant settling thrust and efficient engine thermal conditioning. Pumped idle operation provides vehicle tank prepressurization and maneuver thrust for low g deployment.

This report describes a second iteration of the RL10-IIB heat exchanger investigation program. The design and analysis of the first heat exchanger effort is presented in more detail in FR-18046, Section IV (Reference 1). Testing of the previous design is detailed in FR-19134 (Reference 2).

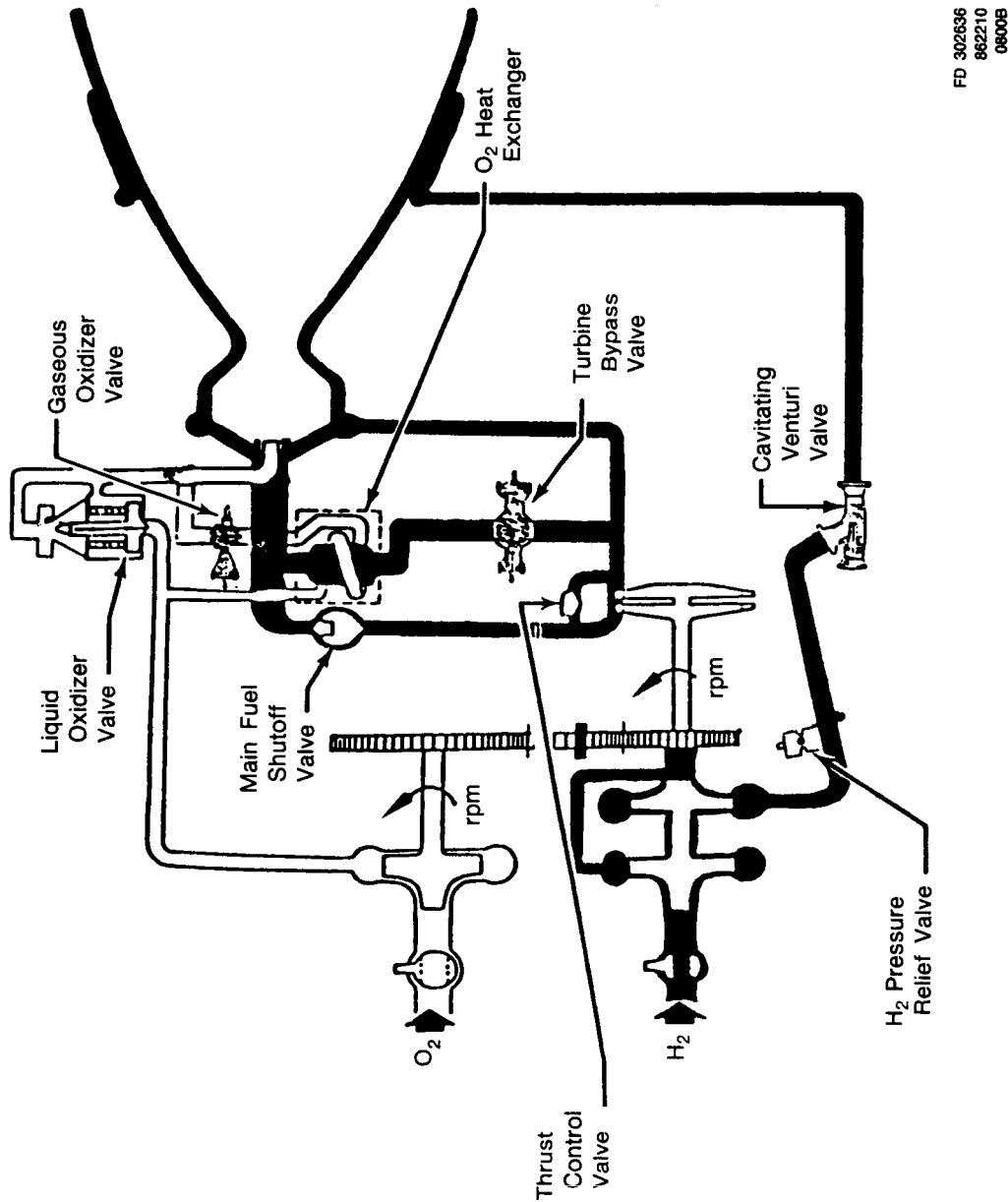
#### **B. PURPOSE**

Stable combustion of the RL10-IIB engine at THI and PI thrust levels can be accomplished by providing gaseous oxygen at the propellant injector. This method of operation eliminates an elaborate engine control system that would otherwise be required during THI operation. Using gaseous hydrogen from the thrust chamber jacket as an energy source, a heat exchanger can be used to vaporize liquid oxygen without creating flow instability. In addition, the heat exchanger can also be used to provide gaseous oxygen for vehicle tank pressurization during full thrust operation. A flow schematic depicting the heat exchanger position in the engine cycle is presented in Figure 1.

#### **C. APPROACH**

Performance, structural, and quality requirements were established by P&W for the RL10-IIB oxidizer heat exchanger (OHE) and are defined in Appendix A, Purchase Performance Specification (PPS) F-654. This specification was used to solicit responses from prominent suppliers experienced in heat exchanger design and manufacturing, which resulted in proposals from two individual firms. The concept discussed herein is identified as a low heat transfer OHE and was proposed by United Aircraft Products (UAP). The remaining design is a concurrent effort incorporating a high heat transfer approach and is presented in P&W Report FR-19289 (Reference 4).

United Aircraft Products has selected the low heat transfer approach in designing the OHE based on previous P&W testing, which showed that excessive heat input contributes to adverse characteristics such as boiling instability and dryout. These characteristics are discussed in detail in this document. At appropriate intervals during the design process, preliminary and critical design reviews were conducted by P&W, during which areas of concern were discussed and potential problems were identified. Additional investigation and analysis were performed where necessary.



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Figure 1. RL10-IIB Engine Flow Schematic

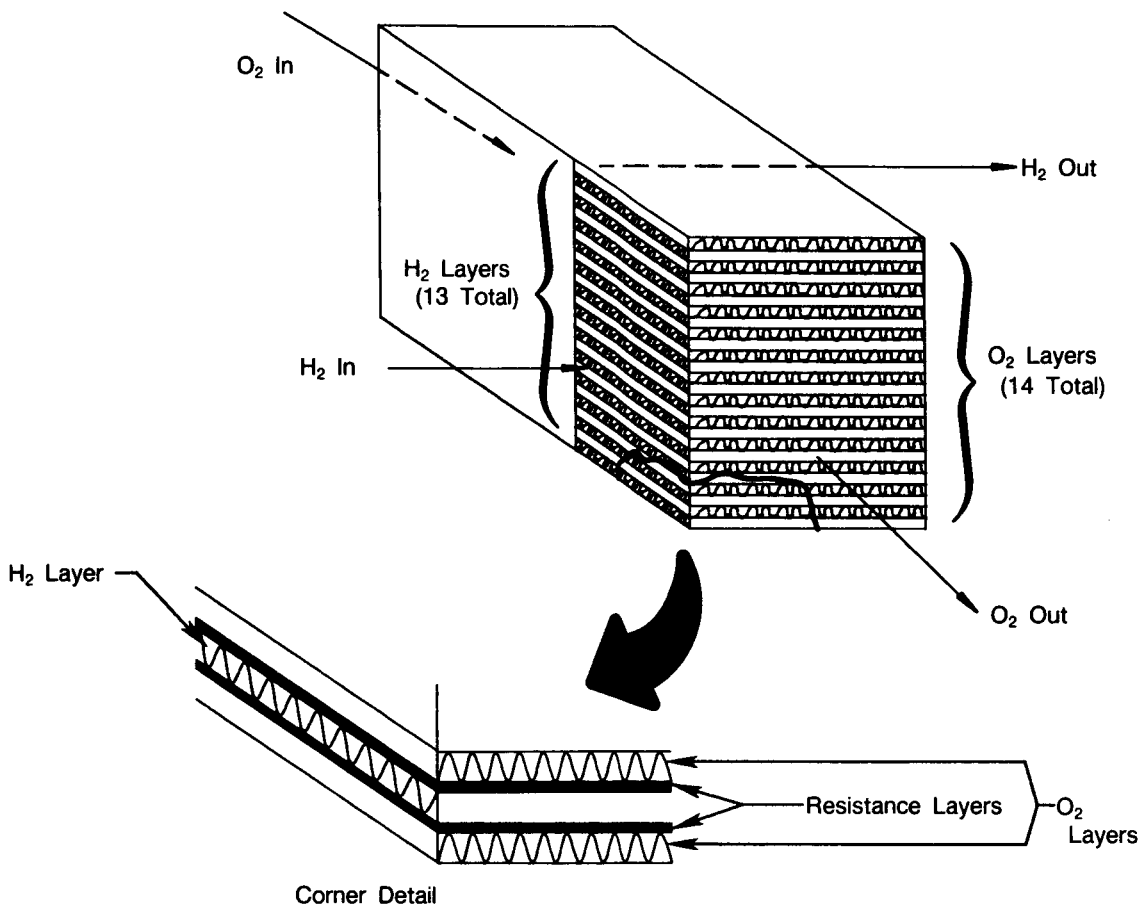


**D. SCOPE**

This report presents the design and analysis of a low heat transfer OHE for the RL10-IIB rocket engine. The design and analysis was completed for P&W by United Aircraft Products in July 1985, and fabrication of two OHE units is in progress at this time. The heat exchanger effort is part of the RL10 Product Improvement Program (PIP). The OHE units will be tested at the component level to verify performance, and then will be mounted on an experimental breadboard RL10-IIB engine for system testing.

## SECTION II DESIGN

The low heat transfer OHE is a cross-counterflow unit using alternating oxygen and hydrogen flowpaths. In a single self-contained unit it completely vaporizes the oxidizer while maintaining low core  $\Delta P$  without inducing pressure oscillations. Plate-fin flowpaths are separated by completely isolated thermal resistance layers to limit heat transfer. The core consists of 13 hydrogen flow layers and 14 oxygen flow layers as shown in Figure 2. A complete description of the unit configuration and fin geometry is contained in Section III of this report.



FDA 308007

Figure 2. Low Heat Transfer Oxidizer Heat Exchanger Core Configuration

Design considerations were focused mainly on the requirements of Preliminary Purchase Performance Specification (PPS) F-654. Two design points, tank head idle and pumped idle, were used as the main criteria for designing the performance characteristics. The OHE unit meets the major design criteria specified by the PPS F-654: minimum pressure drop, stable boiling with minimum pressure oscillations, and no less than 95 percent exit quality. A possible condition of concern is "dryout," where the OHE  $O_2$  passage wall temperature ( $T_{wall}$ ) exceeds the saturation temperature of the fluid ( $T_{sat}$ ) by an excessive amount. In this situation, a thin film of gas is created against the  $O_2$  passage hot wall, severely limiting the heat flux to the flowing liquid.

Such a condition is undesirable, as it could result in less than the required 95 percent O<sub>2</sub> discharge quality. This prompted additional investigation, which is discussed in Section II.B.

High rates of heat transferred to a cryogenic fluid will cause violent boiling, resulting in flow and pressure instability. Previous studies and development reported in FR-7498 (Reference 3) have indicated that stability problems diminish greatly once the oxygen has reached 5 percent quality. Below this level, the heat flux must be limited to 0.5 Btu/sec-ft<sup>2</sup>. The cross-counterflow configuration OHE has been designed to allow maximum heat transfer only after the oxygen has achieved that quality. Also, dense offset fins in the O<sub>2</sub> flow passages will serve to partially counteract possible dryout from localized hot spots, since continued repeated O<sub>2</sub> flow interruption by the offset fin edges would promote liquid-metal contact and minimize dryout-producing gaseous O<sub>2</sub> films. Isolated thermal resistance layers between the hydrogen and oxygen circuits limits heat flux to the calculated required rates throughout the three passes.

The heat exchanger is configured to provide heat transfer in three passes or "stages." The hot hydrogen enters the core in the third stage, turns 180 degrees to proceed through the second stage, and then turns 180 degrees again to flow through the first stage. The oxygen, entering at the opposite end of the core passes through the first, second, and third stages in succession. Temperature gradients between the oxygen and hydrogen are therefore held to a minimum to reduce the possibility of violent boiling and/or dryout.

The Martinelli annular, dispersed flow pattern method (Reference 5) was used to calculate the two-phase flow pressure drops.

## A. THERMAL ANALYSIS

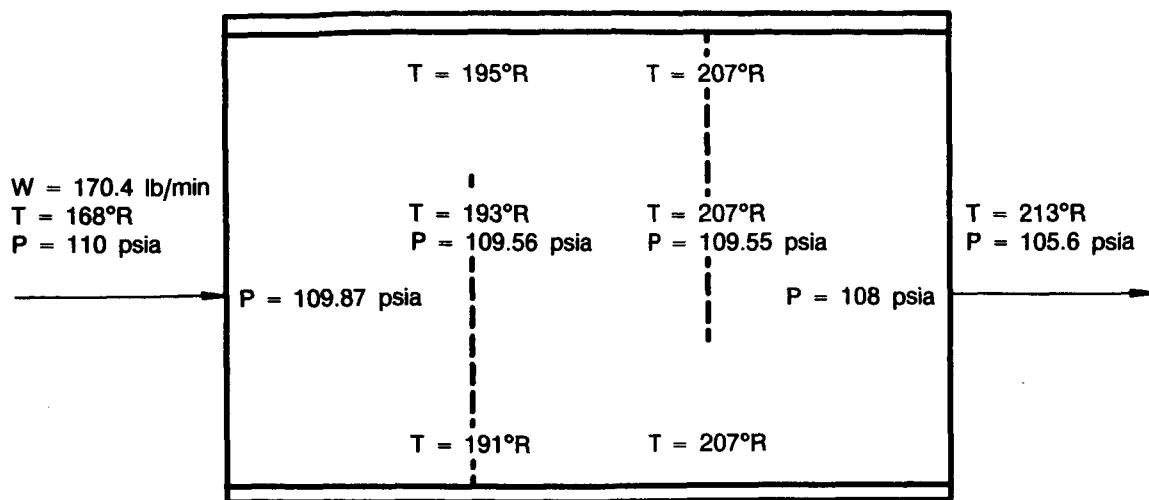
### 1. Pumped Idle Point

Stages 1 and 2 of the heat exchanger heat the oxygen at a controlled rate to saturation temperature at the pumped idle design point. The oxygen convective and boiling film coefficients were combined to obtain the heat transfer coefficient used. A one-dimensional heat transfer analysis determined the amount of heat transfer resistance required, dictating the number and type of fins necessary in the resistance layer. Less thermally conductive plain fins were used in stages 1 and 2 of the hydrogen circuit to minimize pressure drop. Therefore, since the hydrogen releases considerable energy in the previous two stages (stages 3 and 2), an increased density ruffled fin in the stage 1 resistance layer provides the required stage 1 heat flux. For the pumped idle point, the average heat flux is limited to 0.5 Btu/sec-ft<sup>2</sup> in the first two stages, providing 3615 Btu/min of heat transfer. This brings the quality of the oxygen exiting stage 2 to 6 percent.

Stage 3 of the OHE is designed for increased heat input to bring the oxygen to saturated vapor. Temperature and pressure changes in the working fluids as they flow through the stages are illustrated in Figures 3 and 4. High density fins in the resistance layer and offset fins in the hydrogen layers increase the heat flux to 3.3 Btu/sec-ft<sup>2</sup>, which provides approximately 12,000 Btu/min of heat transfer. Table 1 shows a comparison between the required and calculated performance data at the pumped idle design point.

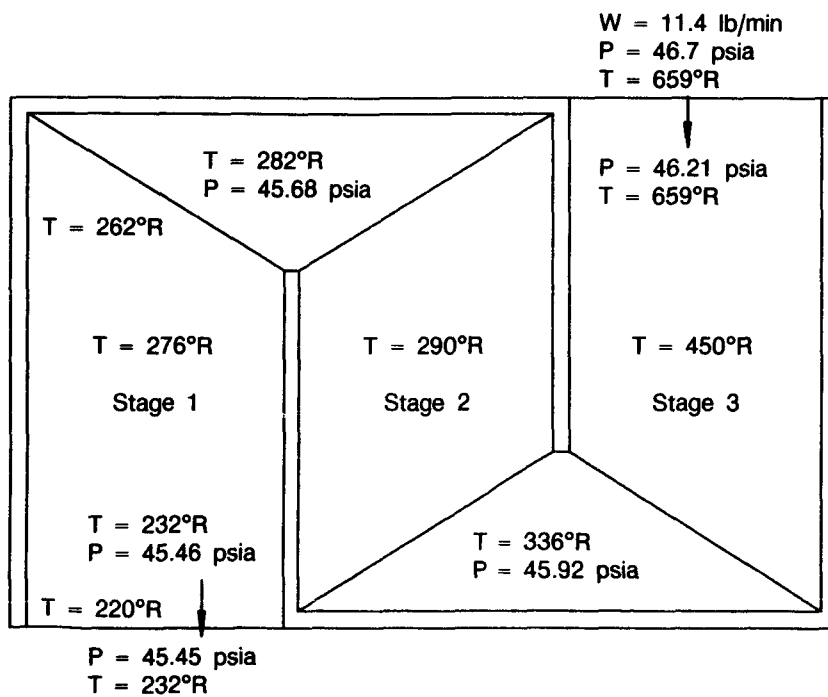
### 2. Tank Head Idle Point

The greatly reduced heat load of the tank head idle design point allows the oxygen to reach 5 percent within the first inch of stage 1. The heat transfer to the oxygen layer is maintained at an average of 0.5 Btu/sec-ft<sup>2</sup>. When it exits stage 3, the oxygen is superheated to 589°R. Table 2 lists the specific conditions at the tank head idle design point.



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Figure 3. Estimated Pressure/Temperature Map for Oxygen Circuit at Pumped Idle



FDA 302638

Figure 4. Estimated Pressure/Temperature Map for Hydrogen Circuit at Pumped Idle

**Table 1. OHE Pumped Idle Design Point Performance**

	Required	Calculated
Heat Load (Btu/min)	16,156	16,156
<i>Hydrogen Circuit</i>		
Flow Rate (lb/min)	11.4	11.4
Inlet Temperature (°R)	659	659
Inlet Pressure (psia)	46.7	46.7
Outlet Temperature (°R)	—	232
Pressure Drop (psid)	2.4 max	1.26
Outlet Pressure (psia)	—	45.44
<i>Oxygen Circuit</i>		
Flow Rate (lb/min)	170.4	170.4
Inlet Temperature (°R)	168	168
Inlet Pressure (psia)	110	110
Outlet Temperature (°R)	—	206
Pressure Drop (psid)	4.7 max	4.4
Outlet Pressure (psia)	—	105.6

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**Table 2. OHE Tank Head Idle Design Point Performance**

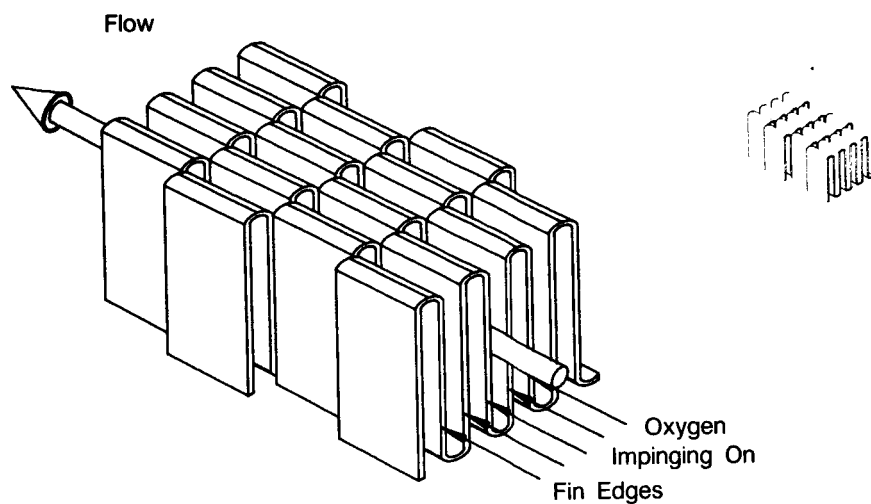
	Required	Calculated
Heat Load (Btu/min)	1686	3417
<i>Hydrogen Circuit</i>		
Flow Rate (lb/min)	5.64	5.64
Inlet Temperature (°R)	594	594
Inlet Pressure (psia)	9	9
Outlet Temperature (°R)	—	416
Pressure Drop (psid)	2.1 max	2.03
Outlet Pressure (psia)	—	6.97
<i>Oxygen Circuit</i>		
Flow Rate (lb/min)	18.6	18.6
Inlet Temperature (°R)	165.8	165.8
Inlet Pressure (psia)	20	20
Outlet Temperature (°R)	—	589
Pressure Drop (psid)	2.3 max	0.5
Outlet Pressure (psia)	—	19.5

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## B. ADDITIONAL ANALYSES

Previous testing and analysis have shown that oxygen dryout initiates when the temperature difference  $T_{\text{wall}} - T_{\text{sat}}$  reaches approximately 30°R. The location where the oxygen inlet manifold and the hydrogen exit manifold meet (ref. cross hatched areas in Figure 7 and 8 in Section III) was identified as a potential hot spot (or localized dryout) area during pumped idle operation. Subsequent analysis revealed a temperature difference along the oxygen wall of  $T_{\text{wall}} - T_{\text{sat}} = 7^{\circ}\text{R}$ , which is regarded as a moderate temperature difference resulting in insignificant pressure fluctuations and flow instability. Also, a potential stage 1 hot spot in the transition area where the hydrogen exits stage 2 was investigated. Results indicated a maximum  $T_{\text{wall}} - T_{\text{sat}}$  of 7.6°R, which again would be of no significant impact. A complete report of the analysis results is contained in Appendix B.

The high average heat transfer rate present in the OHE stage 3 prompted investigation of the possibility of dryout. The average wall-fluid temperature difference is  $T_{\text{wall}} - T_{\text{sat}} = 16^\circ\text{R}$ ; however, a maximum of  $T_{\text{wall}} - T_{\text{sat}} = 50^\circ\text{R}$  was calculated at the hydrogen inlet area, indicating a potential for film boiling (dryout) in that area. However, unobstructed annular or pool flow does not occur, therefore normal film boiling effects exhibited by tube or channel configurations are not expected with this configuration. Instead, the high density offset fin configuration requires oxygen droplets or slugs to continually impinge on the fins, as shown in Figure 5, maintaining heat transfer from fin wall to liquid. Appendix B contains a complete explanation of the dryout potential.



FDA 302639

Figure 5. Oxygen Flow Through Offset Fins

It was suspected that performance would diminish at the extreme outer limits of the engine operating envelope. To investigate this, a sensitivity study was performed to determine the effect of these conditions. Table 3 shows the conditions that were analyzed. Of these conditions, it was determined that pumped idle points 1 and 3 would probably reduce the oxygen exit quality considerably due to the extremely low hydrogen inlet temperatures. The heat exchanger was not designed to operate at these off-design conditions, and later testing will characterize the actual useable operating range of the unit. The remainder of the PI and THI sensitivity points did not significantly affect heat exchanger performance. In addition, hydrogen gas film coefficients and oxygen liquid film coefficients were varied  $\pm 20$  percent. The oxygen boiling film coefficients were varied  $\pm 40$  percent. The study results indicated that the adverse effects of film coefficient variations of these magnitudes were not significant.

**Table 3.** *Oxidizer Heat Exchanger Sensitivity Study Off-Design Points*

<i>Pumped Idle</i>				
<i>Point No.</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>
<b>H<sub>2</sub> Inlet</b>				
W (lb/sec)	0.200	0.144	0.257	0.192
P (psia)	43.0	41.0	55.0	53.0
T (°R)	460.0	774.0	434.0	729.0
<b>O<sub>2</sub> Inlet</b>				
W (lb/sec)	2.15	2.66	2.75	3.39
P (psia)	108.0	102.0	124.0	114.0
T (°R)	168.7	168.0	168.6	167.6
<i>Tank Head Idle</i>				
<i>Point No.</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>
<b>H<sub>2</sub> Inlet</b>				
W (lb/sec)	0.08	0.07	0.12	0.10
P (psia)	7.7	7.4	10.8	10.4
T (°R)	557.0	752.0	519.0	700.0
<b>O<sub>2</sub> Inlet</b>				
W (lb/sec)	0.25	0.27	0.36	0.39
P (psia)	15.6	19.5	21.3	26.6
T (°R)	161.2	165.3	167.1	172.0

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### SECTION III

## OXIDIZER HEAT EXCHANGER CONFIGURATION

The general configuration of the core is a stack of alternating hydrogen and oxygen layers separated by resistance layers. Manifolds provide for the inlet and discharge of each circuit and also for the inlet of the resistance circuit. Heat-treatable aluminum alloys provide the strength needed to withstand anticipated internal pressures and keep the total weight below the specification limit of 70 pounds. Flow passage dimensions, fin types, and overall size were selected to meet the tank head idle and pumped idle design performance points established by PPS F-654. The overall heat exchanger length from flange face to flange face is 26.700 inches; the overall width from flange face to flange face is 17.201 inches. Figure 6 depicts the final oxidizer heat exchanger configuration manifold locations, and overall external dimensions. The unique aspects of the different layers is discussed in detail in the following paragraphs.

The OHE is designed so that construction is accomplished using standard heat exchanger assembly techniques and standard vacuum-furnace brazing processes. This design minimizes the possibility of fabrication problems that could be created by more complex geometries.

### A. OXYGEN CIRCUIT

The oxygen circuit flowpaths run straight through the length of the heat exchanger. Heat transfer is assisted by offset fins 0.252 inch high and 0.006 inch thick, with a density of 28 fins per inch. The fins are enclosed by  $0.252 \times 0.250$  inch separators. Figure 7 presents a schematic representation of the oxygen circuit with approximate overall dimensions. Each oxygen layer is an independent structural unit separated from the surrounding resistance circuit by a 0.020 inch thick tube sheet. The outer oxygen layers (exterior HEX panels) are enclosed by a 0.125 inch thick core sheet.

### B. HYDROGEN CIRCUIT

The hydrogen circuit is arranged in the three-pass configuration illustrated in Figure 8. Changes in flow direction are accomplished by mitered joints within the flowpaths. Fins in the first hydrogen pass are the offset type to provide high heat transfer to complete  $O_2$  vaporization; the second and third pass contain plain fins to provide the required reduced heat transfer to prevent unstable boiling and minimize pressure drop. To minimize flow maldistribution through the mitered joints, offset fins were chosen for these areas. All fins in this circuit are 0.252 inch high and 0.010 inch thick with a density of 8 fins per inch. Approximate dimensions of the flow passages are shown in Figure 8. The fins are enclosed by  $0.252 \times 0.250$  inch separators, and the stages are separated by  $0.252 \times 0.250$  inch separators. The overall width of the  $H_2$  flow passage in the third pass was reduced slightly from that of the first two passes to achieve the necessary heat transfer and flow characteristics.

### C. RESISTANCE CIRCUIT

The resistance circuit between each hydrogen and oxygen layer limits heat transfer between these layers. This cavity is designed to be vented to ambient, which, under operating conditions, would be the vacuum of outer space. In stages 1 and 2, the resistance circuit contains 0.004 inch thick fins installed at 18 fins per inch and 6 fins per inch, respectively. Stage 3 contains 0.010 inch thick plain fins at 28 fins per inch to provide the required higher heat transfer. A void was placed in the ruffled fins at the oxidizer inlet to severely limit heat transfer, as analysis revealed that absolute minimum heat flux would help eliminate instability in this area. These fins are all 0.10 inch high and are enclosed by 0.10 inch high  $\times$  0.250 inch wide separators. A schematic representation of the resistance layer with approximate dimensions is shown in Figure 9. Resistance cavity access is through a manifold spanning the width of the heat exchanger as shown in Figure 6. The interface connection will be a No. 4 AN fitting.



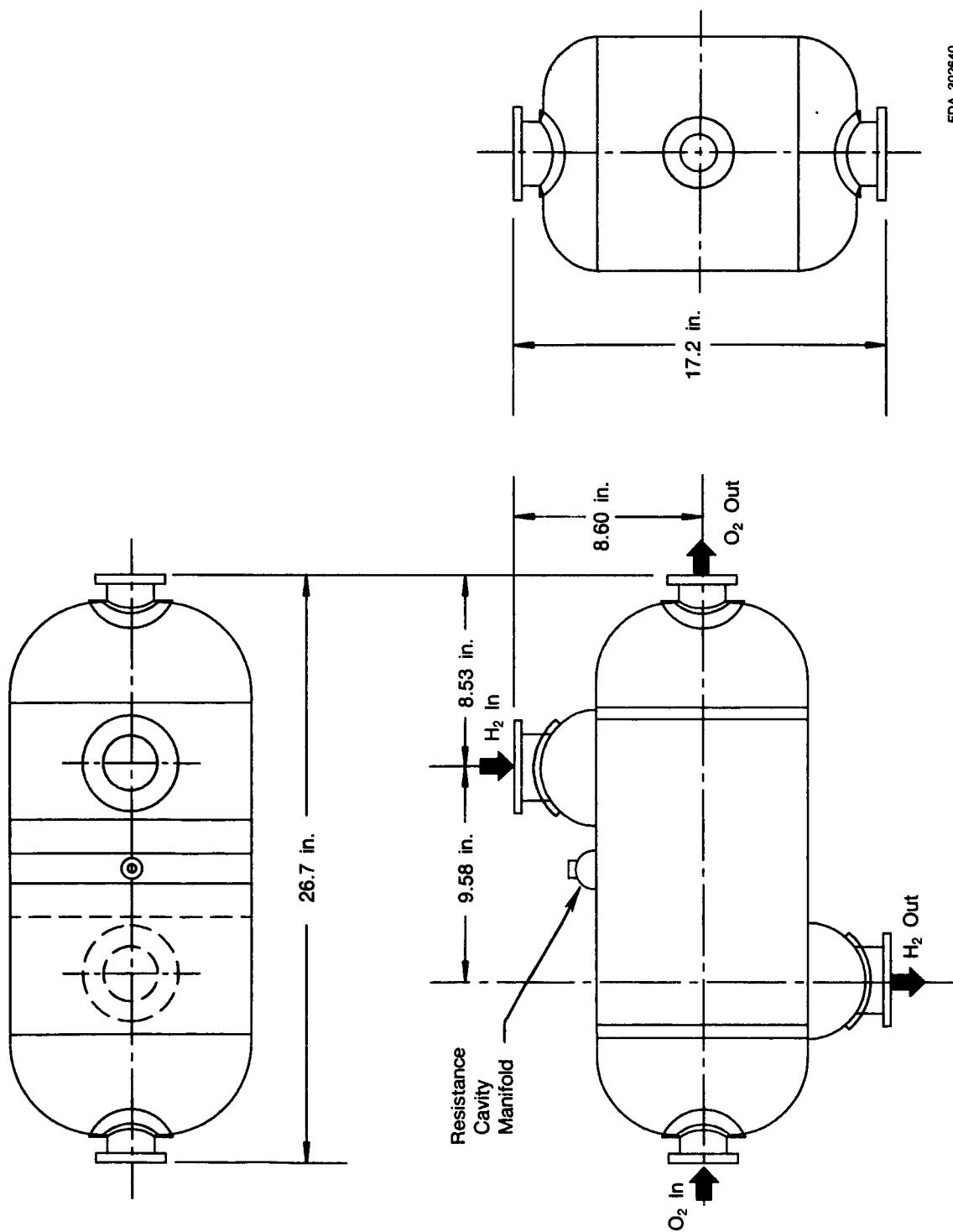
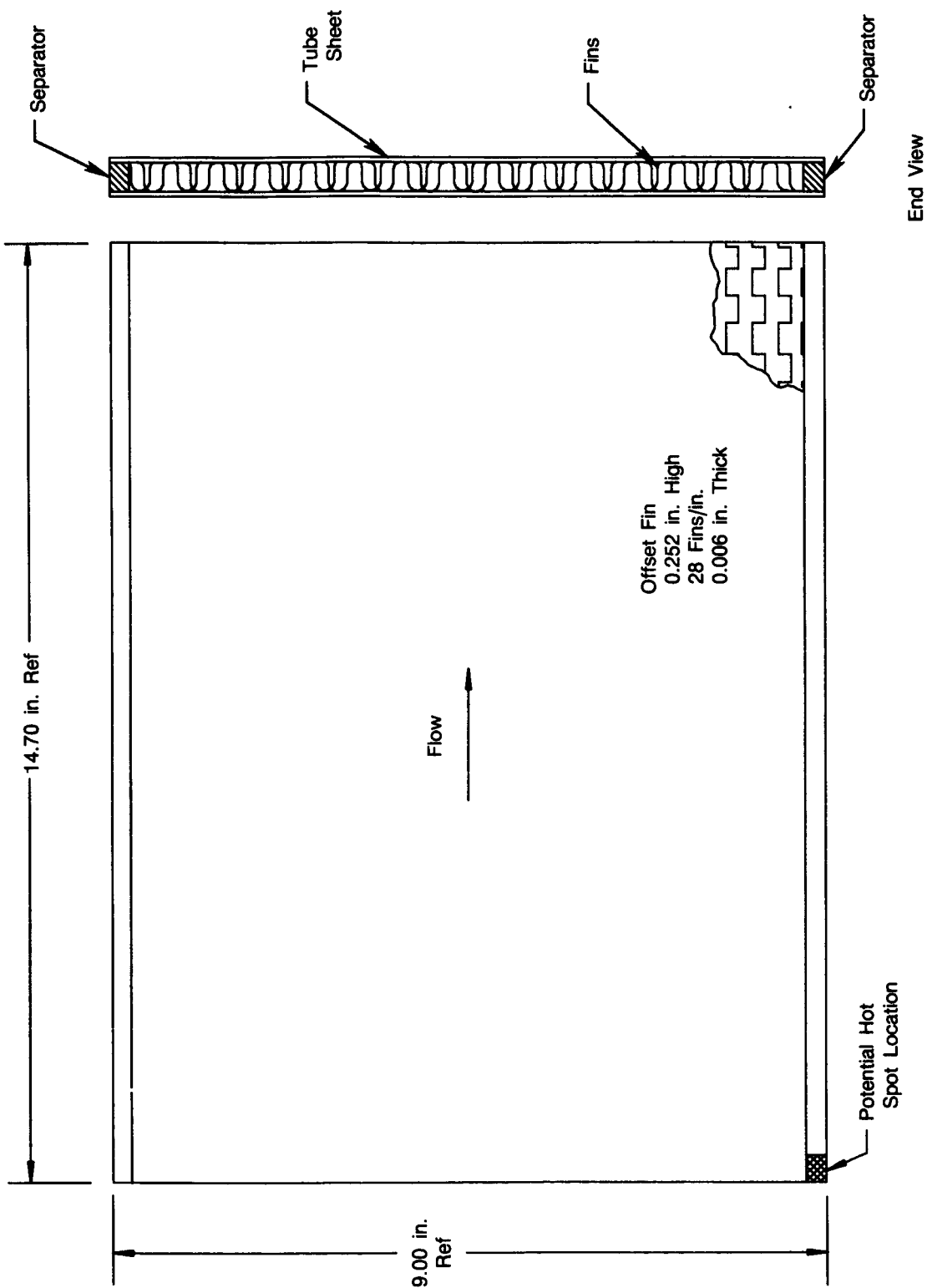
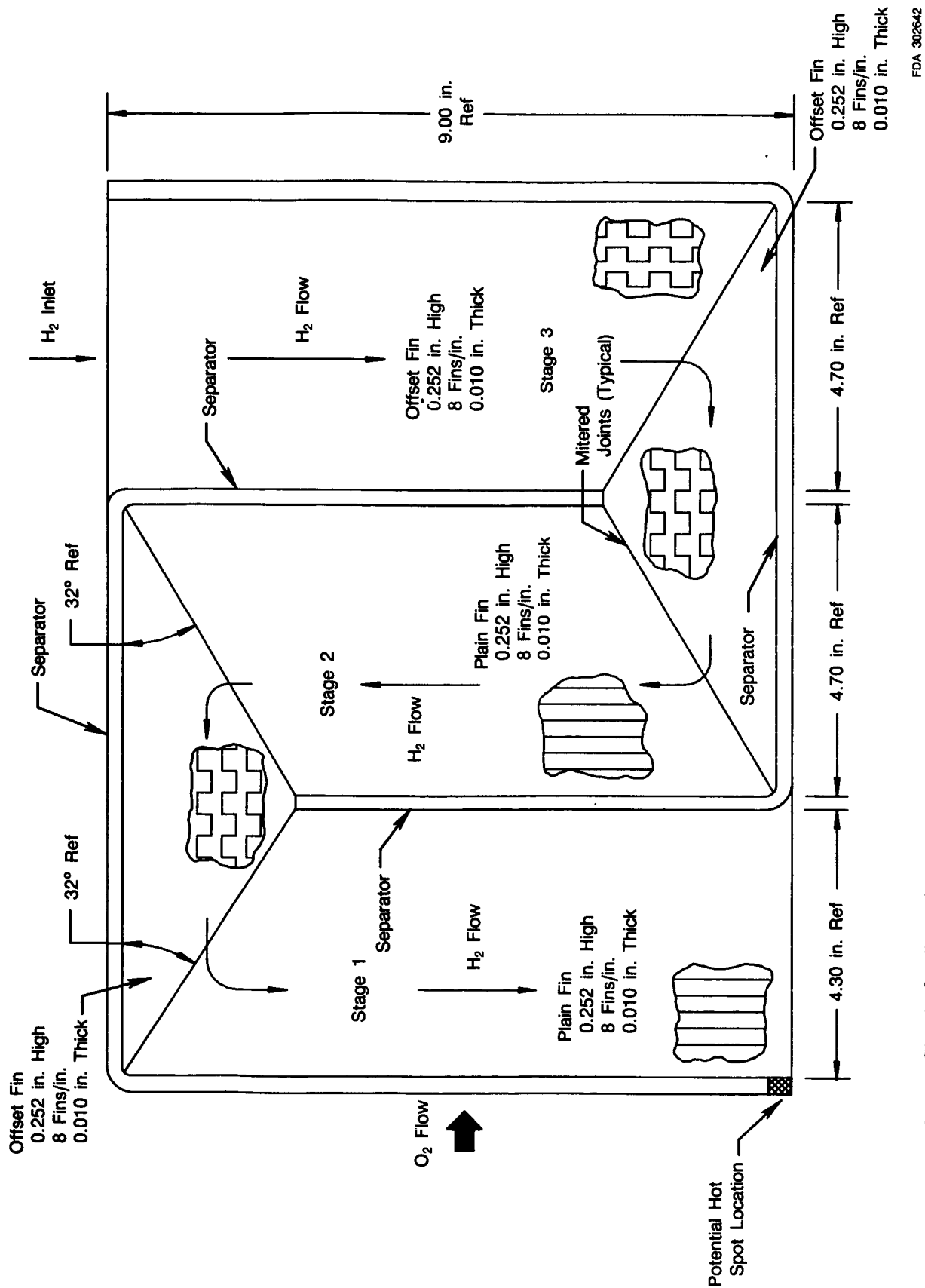


Figure 6. Oxidizer Heat Exchanger External Dimensions



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Figure 7. Oxygen Circuit Configuration



FDA 302642

Figure 8. Hydrogen Circuit Configuration

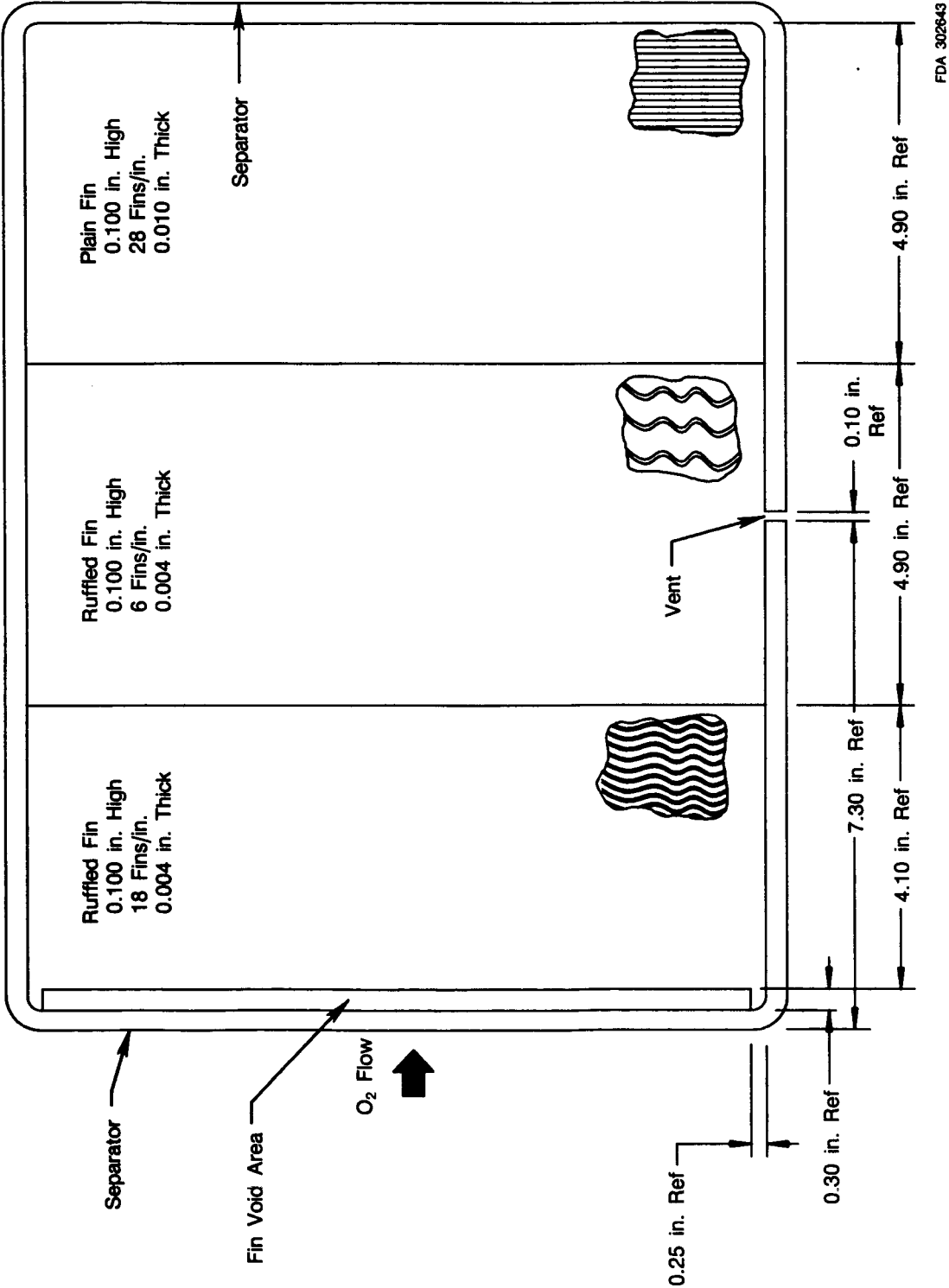


Figure 9. Resistance Circuit Configuration

## D. MATERIALS

The OHE will be fabricated with all-aluminum parts. Alloys for specific parts are listed in Table 4.

**Table 4. Heat Exchanger Alloys**

<i>Part</i>	<i>Alloy</i>
Core Sheets (Exterior Hex Panels)	6061
Tube Sheets	6951
Manifolds	6061
Separators	6063
Flanges	6061
O <sub>2</sub> Layer Fins	6951
H <sub>2</sub> Layer Fins	6951
Resistance Layer Fins	3003
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All alloys except for the resistance layer fins are heat-treatable. The resistance layer material was changed to alloy 3003 from alloy 6951 because of the possibility of incomplete heat treat in this area. Alloy 6951 tends to display intergranular corrosion if post-braze heat treating is not complete.

## E. HEAT TREATMENT

The heat treating process consists of a core solution heat treatment to the T4 condition accomplished by heating the core to approximately 980°F and quenching with a cold water spray. After the manifolds (which are already in a T6 condition) are welded to the core, the entire assembly will be precipitation heat treated to the T6 condition by heating to 320 to 350°F for 8 hours duration.

## F. WEIGHT

The total calculated unit dry weight of the heat exchanger is 69.40 pounds. Of this total, 74 percent is due to the weight of the core and 26 percent is due to manifolds, flanges, and doublers. A weight breakdown by percentage of total is presented in Table 5.

**Table 5. Heat Exchanger Weight Breakdown**

	<i>Percentage of Total</i>
Core	74.0
Core Sheet	4.8
Braze Foil	6.1
Tube Sheet	19.8
Separators	13.7
Fins	29.1
Doubler Strip	0.3
Flanges	3.1
Manifolds	22.6
Doublers	0.4
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A small amount (approximately 2 pounds) of additional weight may be added due to instrumentation for development units.

**G. MOUNTING**

Breadboard engine mounting support will occur primarily at the O<sub>2</sub> flanges. The majority of the weight will be supported by a bracket attached to the O<sub>2</sub> inlet flange at the bottom of the OHE. Additional support and bracing will be provided by the hard plumbing connections to all of the flanges. Since all mounting provisions will be extended to the heat exchanger, no additional mounting hardware will be welded or brazed to the OHE. This mounting configuration is for breadboard test only; additional bracketing may be considered for a flight version OHE.

## **SECTION IV FABRICATION**

Fabrication of all detail parts will be conducted at UAP in Forest, Ohio. Once all parts are completed, the details will be cleaned and stacked into the configuration outlined in Section III. No. 718 braze foil (4047 Aluminum) 0.003-inch thick will be used at the joints, and a load will be applied to the stacked assembly to assure contact at all joints. The fixtured core will then be placed in a furnace for the fluxless vacuum braze process, which will be followed by heat treatment as outlined in Section III.E. After final machining to provide interface dimensions as defined by P&W, a protective alodine coating per AMS 2473 will be applied.

### **A. THERMAL CYCLE**

The completed unit will be subjected to the following thermal cycles. Cold shocking will be accomplished by flowing liquid nitrogen through the oxygen circuit of the heat exchanger until liquid flow is observed from the discharge. It will then be allowed to warm to ambient. This process will be repeated four more times, and will be followed by pressure testing.

### **B. PRESSURE TEST**

Proof pressure will be applied hydrostatically to both circuits at 1100 psia for five minutes. No external or internal leaks at that pressure will be allowed. An external leakage test will be performed at 100 psig gaseous helium pressure. No leakage as indicated by standard leak detector fluid will be accepted. Internal leakage will be checked by pressurizing the oxygen circuit to 100 psig and measuring leakage to the hydrogen circuit. A maximum of 10 sccm of leakage will be allowed.

**REFERENCES**

1. Design and Analysis Report for the RL10-IIB Breadboard Low Thrust Engine, Final Report FR-18046.
2. Oxidizer Heat Exchanger Component Testing, Draft Final Report FR-19134.
3. C. D. Limerick, T. C. Mayes, P. S. Thompson, "Tank Head Idle Oxygen Heat Exchanger Development for Tug Engine," Final Report FR-7498.
4. "High Heat Transfer Oxidizer Heat Exchanger Design and Concept Verification Test Report," Final Report FR-19289.
5. Handbook of Heat Transfer, by Rohsenow and Hartnett, Copyright 1973 by McGraw-Hill.



**APPENDIX A  
PRATT & WHITNEY  
PURCHASE PERFORMANCE SPECIFICATION  
FOR AN OXYGEN/GASEOUS HYDROGEN HEAT EXCHANGER FOR THE RL10-IIB ENGINE**

**1.0 SCOPE**

This specification establishes requirements for an Oxygen/Gaseous Hydrogen Heat Exchanger for the RL-IIB rocket engine. All deviations from the requirements of this specification must be submitted in writing. Approval of deviations by the cognizant P&W Project Engineer must be obtained in writing prior to starting manufacture.

**2.0 APPLICABLE DOCUMENTS****2.1 General**

The following documents which have a specific revision notice shall form part of this specification as shown. When no revision notice is shown, the document in effect on the date of issue of this specification shall apply.

**2.2 Government Documents**

MIL-R-5149B	Rocket Engine, Liquid Propellant, General Specification for
MIL-STD-889B	Military Standard, Dissimilar Materials
MIL-P-25508E-3	Propellant, Oxygen — Type II, Grade A or Equivalent
MIL-P-27201B	Propellant, Hydrogen — Type II or Equivalent
MIL-STD-130A	Identification Marking of U.S. Military Property
DOD-D-1000B	Drawings, Engineering and Associated Lists

**2.3 Non-Government Documents****2.3.1 Industry Specifications**

AMS 2645	Fluorescent Penetrant Inspection
AMS 3159	Leak Test Solution — Liquid Oxygen Compatible
AMS 5620	Bars and Forgings — 13 Cr (0.30 - 0.40C) Free Machining
AMS 5621	Bars and Forgings — 13 Cr (0.30 - 0.40C)
AMS 5630	Bars and Forgings — 17 Cr 0.5 Mo (0.95 - 1.20C)
AMS 5632	Bars and Forgings — 17 Cr 0.5 Mo (0.95 - 1.20C) Free Machining

### 2.3.2 P&W Specifications

PWA 80	Cleaning, wrapping, packaging, and assembly of critical liquid oxygen system parts, assemblies, and components.
PWA 81	Cleaning, wrapping, packing, and assembly of critical liquid hydrogen system parts, assemblies, and components.
PWA 82	Liquid Oxygen Compatibility
PWA 300	Control of Materials and Processes
PWA 382A	Handling of items requiring special protection.
PWA-QA-6076	Supplier Quality Assurance Program Requirements

## 3.0 REQUIREMENTS

### 3.1 Definition

The heat exchanger defined by this specification will be used for the RL10-IIB engine. This engine model is designed to operate in a cryogenic space vehicle which must accomplish engine start at zero gravity without auxiliary propellant settling systems. This results in a wide range of propellant inlet conditions for the engine. The heat exchanger is a key element in assuring its successful operation.

The heat exchanger must gasify the oxygen at low thrust conditions specified herein without creating flow instability. Additionally, the heat exchanger may be used to provide gaseous oxygen for vehicle tank pressurization at full thrust operation. An explanation of the heat exchanger's functions follows.

During tank head idle (THI), the engine operates in a pressurized mode, (i.e., turbopumps not operating) using propellants provided from the vehicle tanks at whatever thermal conditions exist (i.e., superheated gas, saturated gas/saturated liquid of any quality, or subcooled liquid). In this mode, the engine provides approximately 1 percent of full thrust (FT) to the vehicle, which settles the propellants to eventually provide liquid at the engine interface. The liquid to the engine interface will probably not occur simultaneously in the hydrogen and oxygen feed systems.

Due to high density changes between propellant phases, the engine is confronted with significant changes in thrust chamber coolant flow and widely varying combustion mixture ratio which in turn effect combustion temperature. This process must be attenuated. The biggest change in mixture ratio would occur if the oxygen condition changed rapidly and slugs of liquid or pockets of gas were injected into the combustion chamber. This mixture ratio change can be minimized if only gaseous oxygen was available for injection. A similar problem does not occur on the hydrogen system because the hydrogen is always gasified as it cools the thrust chamber tubes before injection into the combustion chamber. Gasification of the oxygen prior to injection will provide a satisfactory level of control. The warm hydrogen gas available after thrust chamber cooling provides a source of energy for gasifying the oxygen in a gaseous hydrogen/oxygen heat exchanger.

With saturated (or subcooled) liquid propellants at the pump interfaces, the engine will be accelerated to 10 percent of rated thrust pumped idle (PI) and operated in this mode to, (1) permit pressurization of the vehicle propellant tanks using hydrogen and oxygen gases bled

from the engine, or (2) satisfy mission requirements where 10 percent maximum thrust is desired. At PI, differential pressure across the oxidizer injector is too low to provide adequate injection velocity for all liquid flow to support stabilized combustion, because the injector area is sized for liquid oxygen injection at full thrust. Injection of lower density gaseous (or mostly gaseous) oxygen increases the velocity, precludes any combustion instability, and increases combustion efficiency (specific impulse). Gaseous oxygen can be supplied by using a hydrogen/oxygen heat exchanger.

Following vehicle tank pressurization, the engine may be accelerated to full thrust. In this mode, the propellant flows bypass the heat exchanger except for a small quantity which is used to gasify oxygen for vehicle tank pressurization purposes.

## **3.2 Characteristics**

The criteria for design of the heat exchanger are shown in paragraph 6.0 of this specification and shall be used as indicated in the following paragraphs.

### **3.2.1 Performance**

This heat exchanger shall be designed to perform at THI and PI. Design for operation at these conditions will provide the performance necessary to satisfy operation at FT, and during the transients between these modes.

#### **3.2.1.1 Heat Transfer Rate**

The heat transfer rate shall be such that vaporization of the oxygen is accomplished without creating unacceptable flow and pressure oscillations due to unstable boiling.

#### **3.2.1.2 Inlet Conditions**

The predicted fluid conditions at the heat exchanger inlets for steady state operation at each design level are shown in paragraphs 6.3 and 6.4.

#### **3.2.1.3 Flow Rates**

The predicted mass flow rates for both fluids are shown in paragraphs 6.3 and 6.4.

#### **3.2.1.4 Pressure Drop**

The maximum allowable pressure drop for each fluid during steady state operation at each design level is shown in paragraphs 6.3 and 6.4.

#### **3.2.1.5 Oscillations**

Oxygen flow oscillations induced by unstable boiling shall be limited to the extent shown in paragraphs 6.3 and 6.4.

#### **3.2.1.6 Oxidizer Discharge Quality**

The required minimum quality of the oxygen which is discharged from the heat exchanger is shown in paragraph 6.5. Complete vaporization is allowable but not required.

### **3.2.1.7 Hydrogen Discharge Temperature**

There are no limits on the temperature of the hydrogen discharged from the unit. The discharge temperature shall be dependent on the heat transfer to the oxygen.

### **3.2.1.8 Pressure**

The proof and burst pressures for each circuit shall be based on FT operation and are shown in paragraphs 6.7 and 6.8.

### **3.2.1.9 Leakage**

There shall be no external leakage allowed when the unit is tested in accordance with paragraph 4.1.2.2.3. Cross circuit leakage shall be checked in accordance with paragraph 4.1.2.2.4 and limited to the extent shown in paragraph 6.6.

## **3.2.2 Physical Characteristics**

### **3.2.2.1 General**

The heat exchanger may be packaged as a single unit or may consist of separate modules to satisfy the design requirements for each engine operating mode. If modules are used, the system shall need no controls to accomplish the required performance at each thrust level.

### **3.2.2.2 Weight**

The weight goal for this heat exchanger is 70 pounds. If a modular system is used, the weight of all interconnecting lines must be included as part of the total heat exchanger weight. The vendor shall identify a weight savings program to reduce the weight for the flight configuration.

### **3.2.2.3 Installation Envelope**

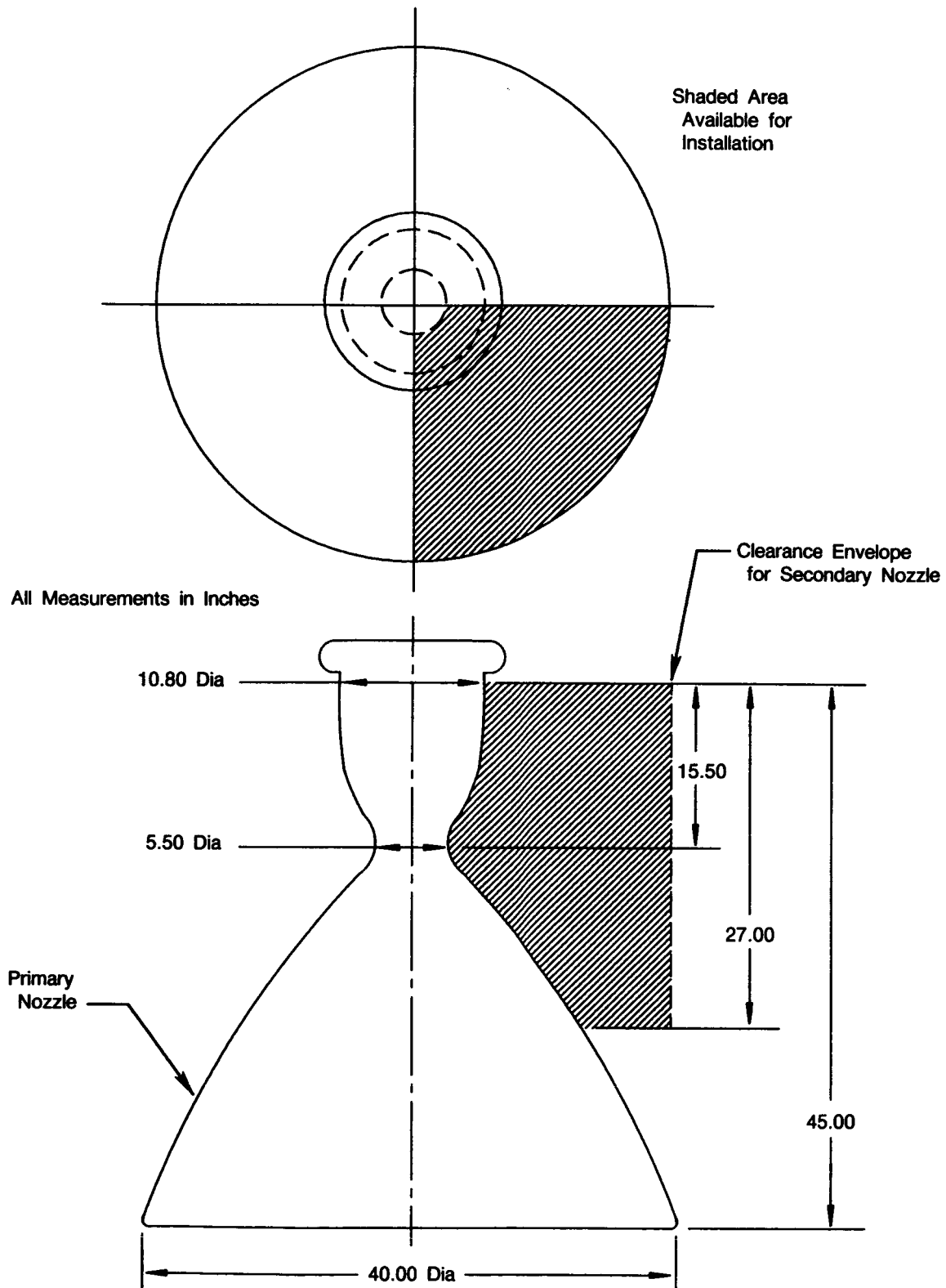
The heat exchanger shall be designed to fit in an envelope between the primary nozzle and the secondary nozzle and must not interfere with translation of the secondary nozzle. Figure A-1 shows approximate dimensions for the primary nozzle and a clearance cylinder for the secondary nozzle. Specific packaging for engine installation will be coordinated with the vendor.

### **3.2.2.4 Interfaces**

The oxygen circuit interfaces shall allow connection to nominal 1.500 in. OD tubing. The hydrogen circuit interfaces shall allow connection to nominal 2.250 in. OD tubing. Interface locations and configurations shall be per sketch CKD 10001.

### **3.2.2.5 Installation**

Provisions for mounting of the heat exchanger shall be coordinated with P&W. Orientation of the unit shall not affect its function.



FDA 307218

Figure A-1. Approximate Dimensions of Primary Nozzle

### **3.2.2.6 Instrumentation**

Provisions shall be made to allow pressure and temperature measurements to be made at various locations in the heat exchanger. The instrumentation is to be used to evaluate the heat exchanger performance. Locations and types of measurements shall be coordinated with P&W and must be approved in writing by the cognizant P&W Project Engineer prior to starting manufacture.

### **3.2.3 Reliability**

The unit shall exhibit no degradation in performance or structural integrity during its duty life. The design goal for duty life of this unit is 300 cycles. The duty cycle for this unit is described in paragraph 7.0.

### **3.2.4 Maintainability**

The unit shall require no service during its duty life in order to maintain performance and structural integrity. The unit shall be designed so that the fluid passages can be cleaned to meet PWA 80 or PWA 81 as applicable. Additionally, the design must allow for dehydration of the fluid passages prior to installation on the engine. The vendor shall prescribe a method for cleaning and dehydration.

### **3.2.5 Environmental Conditions**

#### **3.2.5.1 Altitude**

The unit must be capable of operating at any ambient pressures encountered from sea level to above 100,000 feet.

#### **3.2.5.2 Temperature**

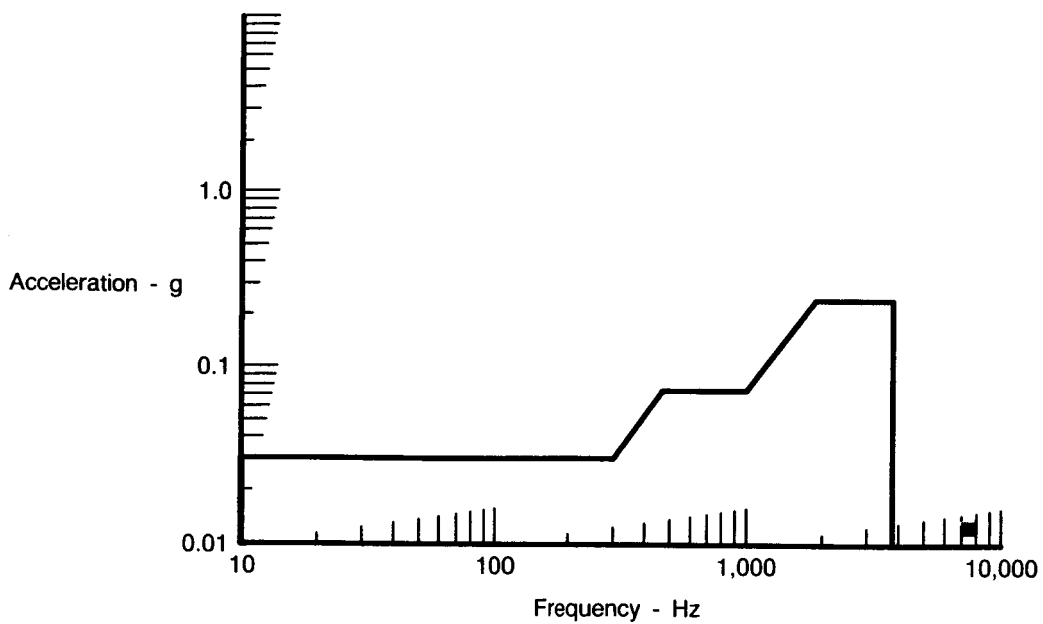
The unit must be capable of enduring storage or operating at any ambient temperature between 100°R and 600°R.

#### **3.2.5.3 Vibration**

The unit shall be designed to withstand the following sinusoidal and random vibration when mounted to simulate engine mounting. At the completion for this testing, there shall be no evidence of damage and the unit shall demonstrate satisfactory operation per paragraph 4.1.2.

##### **3.2.5.3.1 Sinusoidal**

The unit shall be vibrated sinusoidally in each of its principal axes while varying the vibration frequency slowly through the range shown in Figure A-2. All resonant frequencies shall be noted and the unit shall then be vibrated at each of these frequencies along the axis in which the resonance occurred for a period of 15 minutes at the g levels specified in Figure A-2.

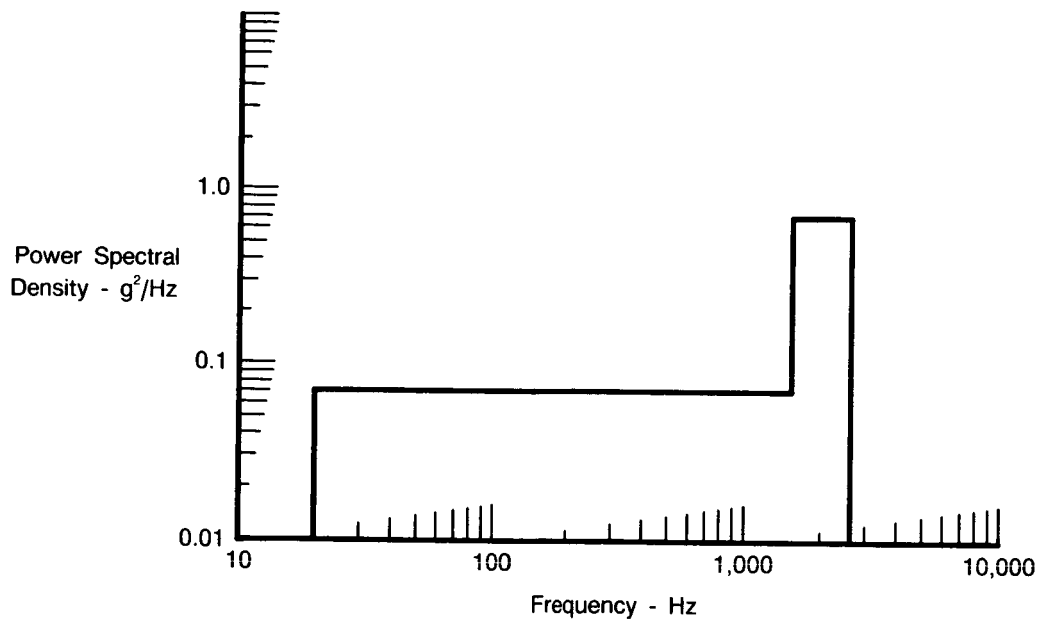


FDA 307219

Figure A-2. Sinusoidal Vibration Schedule

### 3.2.5.3.2 Random

The unit shall be exposed to random vibration as specified in Figure A-3 for 15 minutes in each of its principal axes.



FDA 307220

Figure A-3. Random Vibration Schedule

#### **3.2.5.4 Salt Spray**

The unit must show no degradation in performance or structural integrity after being subjected to a salt spray test per MIL-R-5149B, paragraph 4.9.1.9.6.

#### **3.2.5.5 Gravity/Acceleration**

The heat exchanger performance shall not be affected by changes in gravity or by vehicle acceleration.

### **3.3 Design and Construction**

#### **3.3.1 Materials and Processes**

Materials and processes used in the manufacture of the heat exchanger shall be of high quality and suitable for the purpose. Verification of required material properties of vendor supplied material shall be the responsibility of the supplier, as specified in specification PWA 300. Proof of verification will be supplied to P&W upon request.

##### **3.3.1.1 Material Approval**

All materials selected by the supplier for use in this unit are subject to review and must be approved by the cognizant P&W Project Engineer.

##### **3.3.1.2 Dissimilar Metals**

The use of dissimilar metals as defined in MIL-STD-889B shall be avoided.

##### **3.3.1.3 Use of AMS 5620, 5621, 5630, and 5632 Material**

The use of the subject heat treatable stainless steels, or equivalents, is prohibited unless agreed to in writing by the cognizant P&W Project Engineer.

##### **3.3.1.4 Material Compatibility**

All materials used in construction shall be compatible with the fluids carried by the heat exchanger such that there shall be no degradation of material or fluid properties as a result of long term contact. Any materials known to be susceptible to stress corrosion shall not be used. All materials used in the oxygen circuit shall be proven to be compatible with liquid oxygen as demonstrated by compliance with specification PWA 82.

##### **3.3.1.5 Standards**

Materials and processes which are listed in the latest edition of the SAE Aerospace Materials Specification index or which are controlled by P&W specifications shall be used whenever possible. AN, MS, or MIL standard parts shall be used, wherever possible, and identified by their standard part number. MS, AND, and AS design standards shall be used wherever applicable.



**3.3.2 Marking**

Part identification shall be in accordance with MIL-STD-130F and shall include at least the following:

1. Manufacturer's Name
2. Manufacturer's Part Number and latest change identification
3. Manufacturer's Serial Number
4. P&W Part Number and latest change identification
5. P&W Serial Number.

**3.3.3 Quality Assurance**

The supplier quality assurance program shall comply with the requirements of PWA QA-6076, Section III.

**3.3.4 Interchangeability**

All parts having the same manufacturer's part number shall be functionally and dimensionally interchangeable with each other with respect to installation and performance.

**3.3.5 Changes in Design**

All changes made in design, material, or manufacturing processes after initial acceptance must be approved in writing by the cognizant P&W Project Engineer.

**3.4 Documentation****3.4.1 Design Analysis**

The analysis of the design of the heat exchanger shall be available for review and must be approved by the cognizant P&W Project Engineer prior to start of fabrication of the first unit. The analysis shall include both the thermal and structural aspects of the design. All supporting test data, previous experience, or other background used as rationale for the concept selection shall also be presented. The analysis must be updated as required to support subsequent changes in design or manufacturing processes. These updates must be reviewed and approved by the cognizant P&W Project Engineer prior to incorporation of such changes.

**3.4.2 Drawings**

All drawings for the heat exchanger shall be prepared in accordance with Military Specification DOD-D-1000B. The supplier shall supply three copies of all drawings necessary to describe the unit. All subsequent changes must be coordinated with and approved by the cognizant P&W Project Engineer.

**3.5 Precedence**

In the event of conflict between this specification and referenced documents, this specification shall take precedence.

## **4.0 QUALITY ASSURANCE PROVISIONS**

### **4.1 General**

The supplier shall be responsible for compliance with all quality assurance provisions of this specification and all referenced specifications unless agreed to in writing by the cognizant P&W Project Engineer.

#### **4.1.1 Responsibility for Tests**

Unless otherwise agreed to, the supplier shall be responsible for all tests specified herein.

#### **4.1.2 Tests and Examinations**

##### **4.1.2.1 Performance Tests**

The supplier shall demonstrate the performance of the heat exchanger for compliance with paragraphs 3.2.1.4, 3.2.1.5, and 3.2.1.6 based on conditions shown in paragraphs 3.2.1.2 and 3.2.1.3. This test must be performed for every development unit and for the first and every tenth unit of any production lot. If the production lot is less than ten, the test shall be performed for the first and last units of the lot. The fluids used for this testing need not be hydrogen and oxygen, but must be suitable to demonstrate the performance of the heat exchanger for the design fluids. The test program, including predicted results, must be submitted for approval by the cognizant P&W Project Engineer at least 45 days prior to the first test.

##### **4.1.2.2 Acceptance Tests**

Each unit shall be subject to the following tests prior to delivery. These tests are to be performed in the order listed unless agreed to by the cognizant P&W Project Engineer. The test procedure shall be submitted to and approved by the cognizant P&W Project Engineer prior to beginning testing. Any subsequent changes must also be approved by the cognizant P&W Project Engineer.

###### **4.1.2.2.1 Thermal Cycle**

Each unit shall be subjected to thermal cycle testing. The oxygen circuit inlet shall be connected to a liquid nitrogen source and flow shall be initiated at  $20 \pm 2$  psia. Continue flow until liquid is observed from the oxygen discharge port, and maintain for one minute following establishment of liquid flow. Following this, the unit shall be allowed to warm to ambient. Return to ambient can be assisted by an ambient gas purge which shall not return the unit to ambient in less than 15 minutes. This thermal cycle shall be repeated four additional times. The heat exchanger shall suffer no damage or permanent deformation, and shall meet leakage requirements when tested per paragraphs 4.1.2.2.3 and 4.1.2.2.4.

###### **4.1.2.2.2 Proof Test**

Each unit shall be subject to a proof test at the pressure levels indicated in paragraph 6.7. Pressure is to be held for a minimum of 5 minutes. The unit shall exhibit no permanent deformation and shall meet leakage requirements when tested per paragraphs 4.1.2.2.3 and 4.1.2.2.4.

#### **4.1.2.2.3 External Leak Test**

Each unit shall be subject to a test for external leakage. The unit shall be pressurized to 100 psig with gaseous helium and checked for external leaks. No external leakage is allowed as indicated by standard leak detector fluid (ASM 3159 or equivalent).

#### **4.1.2.2.4 Internal Leak Test**

Each unit shall be subjected to a test for internal leakage. The oxidizer circuit shall be pressurized to 100 psig with gaseous nitrogen. A leakage measuring device shall be connected to the hydrogen circuit. Pressure must be maintained for a minimum of 5 minutes. Leakage shall be limited to the extent shown in Paragraph 6.6.

#### **4.1.2.2.5 Fluorescent Penetrant Inspection**

All external welds and surfaces shall be inspected in accordance with AMS 2645 or equivalent. There shall be no evidence of cracks, pits, or porosity. Caution: Oil based penetrants shall not be used.

### **4.3 Test Data Reports**

#### **4.3.1 Performance Test Report**

The supplier shall submit a written report of the performance test results and data analysis within 60 days of test completion.

#### **4.3.2 Acceptance Test Report**

The supplier shall supply one copy of the acceptance test data with each unit procured under this specification. This data must be provided at the time the unit is delivered to Pratt & Whitney.

## **5.0 PREPARATION FOR DELIVERY**

### **5.1 Dehydration**

The unit shall be dehydrated prior to shipment by a method prescribed by the supplier. This procedure shall be subject to review and must be approved by the cognizant P&W Project Engineer prior to shipment.

### **5.2 Shipping Closures**

The unit must be packaged to prevent damage during shipment. Packaging shall be in accordance with PWA 382A.

## **6.0 DESIGN CRITERIA**

### **6.1 General**

The criteria shown here are to be used in conjunction with Section 3.0 of this specification as the basis for design of the heat exchanger.

## **6.2 Fluids**

### **6.2.1 Hydrogen**

Gaseous hydrogen per MIL-P-27201B.

### **6.2.2 Oxygen**

Liquid oxygen per MIL-P-25508E-3.

## **6.3 Tank Head Idle Criteria**

### **6.3.1 Hydrogen Inlet Conditions**

Pressure: 9.0 psia  
Temperature: 594°R.

### **6.3.2 Oxygen Inlet Conditions**

Pressure: 20 psia  
Temperature: 165.8°R.

### **6.3.3 Allowable Pressure Drops**

Hydrogen: 2.1 psi maximum  
Oxygen: 2.3 psi maximum.

### **6.3.4 Flow Rates**

Hydrogen: 0.094 lbm/sec  
Oxygen: 0.31 lbm/sec.

### **6.3.5 Allowable Oxygen Flow Oscillations**

0.05 lbm/sec.

## **6.4 Pumped Idle Criteria**

### **6.4.1 Hydrogen Inlet Condition**

Pressure: 46.7 psia  
Temperature: 659°R.

### **6.4.2 Oxygen Inlet Conditions**

Pressure: 110 psia  
Temperature: 168°R.

### **6.4.3 Allowable Pressure Drops**

Hydrogen: 2.4 psi maximum  
Oxygen: 4.7 psi maximum.

#### **6.4.4 Flow Rates**

Hydrogen: 0.190 lbm/sec  
Oxygen: 2.84 lbm/sec.

#### **6.4.5 Allowable Oxygen Flow Oscillations**

0.20 lbm/sec.

#### **6.5 Oxidizer Discharge Quality**

0.95 minimum.

#### **6.6 Allowable Cross Circuit Leakage**

10 sccm.

#### **6.7 Proof Pressure**

1100 psia.

#### **6.8 Burst Pressure**

1500 psi.

#### **6.9 Maximum Cross Circuit Differential Pressure**

300 psi.

### **7.0 DUTY CYCLE**

#### **7.1 General**

The duty cycle for the unit shall consist of operation at tank head idle, pumped idle, and full thrust levels as described below.

#### **7.2 Tank Head Idle**

##### **7.2.1 Prestart**

The unit will be at ambient pressure and temperature prior to start.

##### **7.2.2 Start to Tank Head Idle**

Pressurization of the unit to THI levels will occur within 0.5 second of propellant flow start.

##### **7.2.3 Tank Head Idle Operation**

Hydrogen and oxygen flows will be maintained at THI pressures until the engine temperatures stabilize. This can be from 20 to 180 seconds depending on the fluid conditions at the engine inlets.

### **7.3 Pumped Idle**

#### **7.3.1 Transition**

Transition from the THI to PI will take place within 0.7 second from the time the signal is given.

#### **7.3.2 Pumped Idle Operation**

The unit will operate at PI for a minimum of 5 seconds and a maximum of 3600 seconds.

### **7.4 Full Thrust**

#### **7.4.1 Transition**

Transition to the FT operating pressures will take place within 0.4 second from the time the signal is given.

#### **7.4.2 Full Thrust Operation**

The unit can operate at FT for as long as 1200 seconds.

### **7.5 Shutdown**

Engine shutdown and ventage of the heat exchanger fluids can occur from any thrust level. Venting will take place within 0.25 second from the time the signal is given.

APPENDIX B

ENGINEERING REPORT 1922  
TEMPERATURE ANALYSIS FOR  
UA538949-1  
OXYGEN/GASEOUS HYDROGEN HEAT EXCHANGER

Prepared For  
PRATT AND WHITNEY AIRCRAFT  
WEST PALM BEACH, FLORIDA

Project 4357

May 3, 1985

Prepared By

Max Wiard  
M. R. Wiard  
Engineering Department

Approved By

J. E. Wunder  
J. E. Wunder  
Engineering Department

UNITED AIRCRAFT PRODUCTS, INC.

Post Office Box 1335  
Dayton, Ohio 45401

Post Office Box 37  
Forest, Ohio 45843

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**Edited by: P. G. Kanic  
Pratt & Whitney  
West Palm Beach, Florida**



The purpose of this report is to respond to the action items established in the RL10 PDR, dated March 21, 1985. The action items addressed are:

- Manifold Hot and Cold Corner Analysis
- Stage 1 Hot Spot Analysis
- Stage 3 Burn Out/Dry Out Analysis
- Pressure and Temperature Map

The maximum temperature difference between the heat exchanger wall and the saturation temperature of the oxygen ( $T_w - T_{sat}$ ) that would constitute a dangerous hot spot and the size of area that this temperature difference has to cover before it creates flow instabilities and pressure pulses at the oxygen exit are not known quantitatively. Also there are no data or correlations on these critical heat fluxes for the high density fin used in the oxygen circuit.

A heat flux of  $Q/A = 0.5 \text{ Btu/sec-ft}^2$  was the criteria used in the heat exchanger design to size Stages 1 and 2, since this was the recommended level concluded in P&W FR-7498 (i.e., Reference 3). This report also indicates transient heat transfer rates "much higher" than  $Q/A = 0.5 \text{ Btu/sec-ft}^2$  were tested with flow stability. Using the  $Q/A = 0.5 \text{ Btu/sec-ft}^2$  heat flux criteria and back calculating ( $T_w - T_{sat}$ ) from the boiling heat transfer curve (Figure III-13 of P&W FR-7498) yields  $T_w - T_{sat} = 5.6^\circ\text{R}$ . Twice this heat flux yields  $T_w - T_{sat} = 7.5^\circ\text{R}$ . It is suspected that over small areas higher temperatures could be sustained without excessive flow instabilities since the oxygen circuit fin will have a stabilizing effect as the fin offsets act as baffles to "break-up" pressure pulses. The magnitude of this "higher temperature" is not known.

#### MANIFOLD HOT AND COLD CORNER ANALYSIS

The corner of the heat exchanger where the oxygen inlet manifold and the hydrogen exit manifold are contiguous could create a hot spot that might cause excessive nucleate boiling of the subcooled oxygen resulting in flow instabilities.

Figure B-1 is a sketch of this area. This picture shows how the hydrogen and oxygen manifolds, the oxygen circuit nosepieces, and the resistance layer and hydrogen circuit nosepieces meet to form a common solid block (shaded area). The heat transfer into this block from the hot hydrogen to the hydrogen nosepieces and the oxygen manifold are of interest in this analysis.

To simplify the manifold analysis, the temperature distribution in the hydrogen and resistance layer nosepieces were investigated first. The results of this analysis was used in the manifold analysis. Figure B-2 shows the model used and the resulting calculated temperature distribution in the nosepieces from a finite-difference analysis. The fluid temperatures and the heat transfer coefficients used for the analysis are indicated on Figure B-2. The result of this part of the analysis show that the temperature difference on the front of the nosepieces is  $T - T_{sat} = 5^\circ\text{R}$  which results in a heat flux  $Q/A = 0.67 \text{ Btu/sec-ft}^2$ . This is higher than the heat flux of  $Q/A = 0.5 \text{ Btu/sec-ft}^2$  that was the criteria used for the stage one and two oxygen circuit design but with the moderate five degree temperature difference major flow fluctuations are not anticipated. Any local pressure disturbances and/or flow fluctuations generated on the nosepieces or in the manifold will stabilize on entering the high fin density oxygen circuit.

Figure B-3 shows the model used and the resulting calculated temperature distribution based on a finite-difference analysis in the area where the hot and cold manifolds are contiguous. The temperature difference  $T - T_{sat} = 7^\circ\text{R}$ . The calculated heat flux in this area is  $Q/A = 0.99 \text{ Btu/sec-ft}^2$ . As stated above with this moderate temperature difference, flow fluctuations and pressure disturbances should not be propagated upstream in the high fin density oxygen circuit. The high density fin used in the oxygen circuit will be discussed in detail under Stage 3 Burn Out/Dry Out Analysis.

## STAGE 1 HOT SPOT ANALYSIS

The heat transfer model used for the Stage 1 Hot Spot Analysis is shown in Figure B-4. This sketch shows the fluid temperatures and the heat transfer coefficients used to calculate the temperature distribution in the tube sheets and fins. The temperature of the tube sheet separating the hydrogen circuit and the resistance layer ( $T = 195^{\circ}\text{R}$ ) was calculated on the basis of one dimensional heat transfer from the hydrogen circuit to the tube sheet by convection. The temperature distribution across the resistance fins, through the tube sheet separating the resistance layer and the oxygen circuit, and in the oxygen fin was based on a two-dimensional finite-difference analysis.

The area of the first stage investigated for potential hot spots is the upper corner of the unit where the hydrogen leaves the second stage and passes counterflow to the first stage. This area would represent the worst case since it has the highest temperature differential between the oxygen and hydrogen. If hot spots were to occur, they would show up on the tube sheets. A maximum  $T_w - T_{\text{sat}} = 7.6^{\circ}\text{R}$  is indicated on Figure B-4 (i.e.  $175.6^{\circ}\text{R}$  minus  $168^{\circ}\text{R}$ ). The results of this analysis indicates hot spots in Stage 1 will not be a problem.

## STAGE 3 BURN OUT/DRY OUT ANALYSIS

Published correlations to predict critical heat flux are mostly for pool boiling. Test data and correlations for forced convection consist mainly of uniformly heated test sections for flow inside round tubes, rectangular channels, and annuli. The correlations for forced convection tube flows are sensitive to geometry, fluids, test setup, flow conditions, as well as heat fluxes and temperature differences. Since no forced convection critical heat flux correlations have been established that apply universally to all fluids and geometries, the following explains the design rationale for the third stage of the RL-10 heat exchanger.

### The Dry Wall (Burn Out)

The third stage of this heat exchanger has a high average heat flux ( $Q/A = 3.5 \text{ Btu/sec-ft}^2$ ) and an average temperature difference ( $T_w - T_{\text{sat}} = 16^{\circ}\text{R}$ ). In the area where the hydrogen enters the core the calculated temperature difference between the wall and the oxygen is  $T_w - T_{\text{sat}} = 50^{\circ}\text{R}$ , with a heat flux  $Q/A = 4.2 \text{ Btu/sec-ft}^2$ . In the area where the hydrogen leaves the third stage, the calculated temperature difference is  $T_w - T_{\text{sat}} = 11^{\circ}\text{R}$  with a heat flux of  $Q/A = 0.68 \text{ Btu/sec-ft}^2$ . At the inlet, the temperature difference is in the range that separates the nucleate boiling regime from the film boiling regime as indicated in Figure III-13 of P&W FR-7498. This correlation is for oxygen pool boiling, not forced convection flow. Nevertheless, it indicates that film boiling and the associated low heat transfer could exist in this area of the heat exchanger.

It is doubtful that the classical flow regimes (bubble, slug, annular, and mist) characteristic of forced convection in tubes will develop or exist in any systematic way in the plate-fin heat exchanger for the RL-10 due to the high density fin, the low Length/Diameter ratio ( $L/D$ ) fin configuration and the ability of the oxygen to flow laterally in the offset fin. Figure B-5 is a sketch of the fin used in the oxygen circuit. The fin is 0.252 inch high, with 28 fins/inch density, and 0.125 inch offset. Each stage of the heat exchanger has over 10,000 individual fins. The fin length/hydraulic diameter ratio is 2.3.

The classical model depicting heat transfer in film boiling (mist flow) allows heat transfer from the hot wall to the vapor, and after the heat has been transferred into the vapor core, it is transferred to the liquid droplets. This type of heat transfer results in low heat transfer coefficients. It is hypothesized that in the RL-10 unit, the liquid droplets will persist in wetting the fins due to the short fin length, the large number of fins in the flow path, and the potential for the liquid droplet to flow laterally, thus, continually impinging on the fins. The compact fin

arrangement will minimize the dryout potential normally exhibited in tube and channel geometries and result in a higher heat transfer coefficient than that obtained from conventional film boiling.

### Margin of Safety in RL-10 Heat Exchanger Third Stage Design

The specification requires an oxygen exit quality of 95% minimum. This would require a total of  $Q = 15,489$  Btu/min for the three stages. Stage 1 and 2 are designed to transfer 3,615 Btu/min, this leaves  $Q = 11,874$  Btu/min for the third stage to obtain the 95% quality. Using the calculated heat transfer coefficient for the hydrogen circuit of  $215$  Btu/hr-ft<sup>2</sup>-°R results in requiring an oxygen heat transfer coefficient of  $167$  Btu/hr-ft<sup>2</sup>-°R to transfer the  $Q = 11,874$  Btu/min.

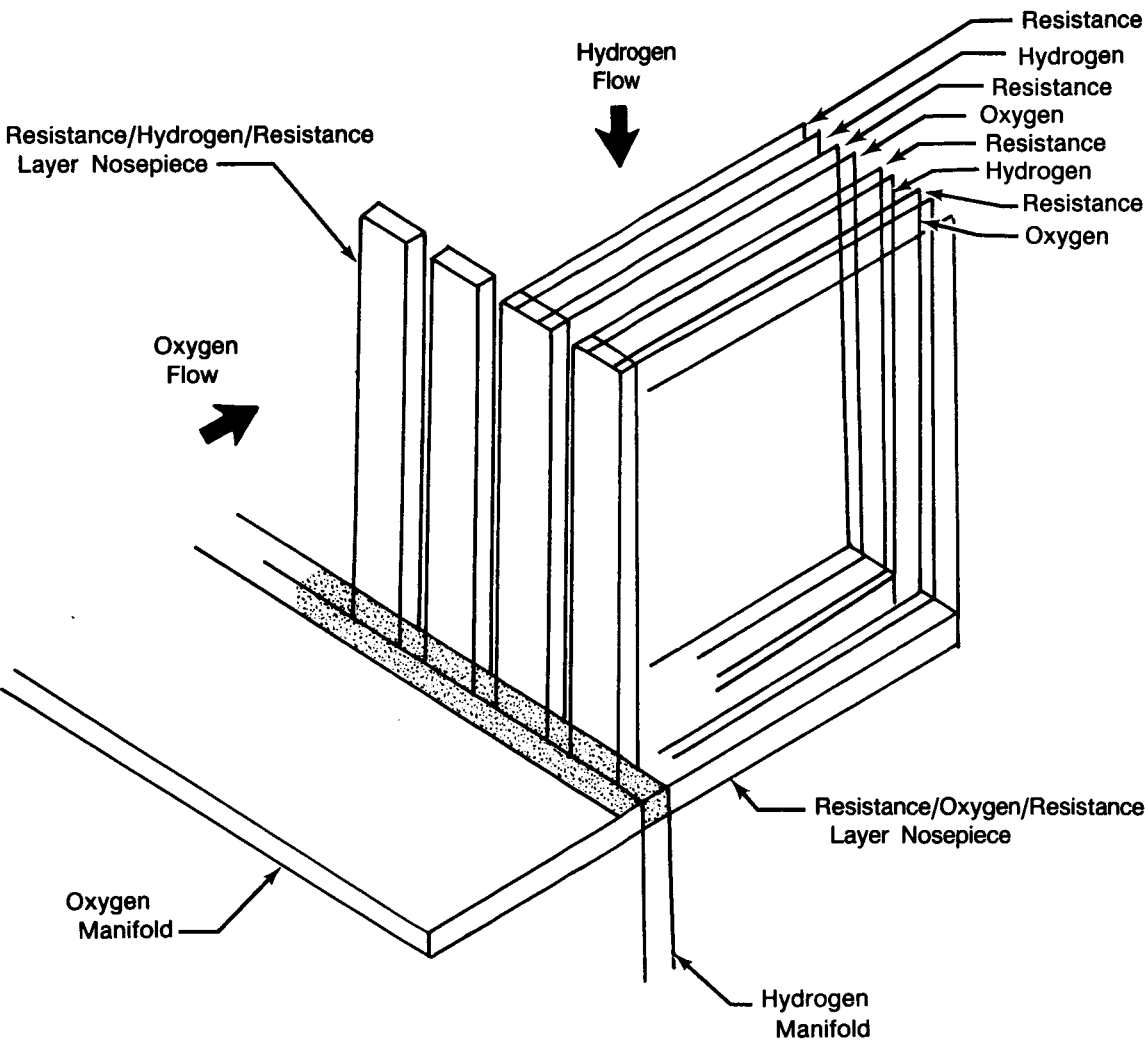
The calculated heat transfer for the RL-10 development unit is  $Q = 17,083$  Btu/min.  $Q = 13,468$  Btu/min of the total is accomplished in the third stage. This represents six degrees of super heat in the oxygen at exit. This was based on a third stage heat transfer coefficient for the hydrogen circuit of  $215$  Btu/hr-ft<sup>2</sup>-°R and the oxygen circuit heat transfer coefficient of  $977$  Btu/hr-ft<sup>2</sup>-°R. The oxygen circuit heat transfer coefficient is the sum of the boiling coefficient ( $1,577$  Btu/hr-ft<sup>2</sup>-°R) and the liquid convection coefficient ( $284$  Btu/hr-ft<sup>2</sup>-°R) averaged with the gas convection coefficient ( $94$  Btu/hr-ft<sup>2</sup>-°R); e.g.  $(1577 + 284 + 94)/2$ .

The sum of the liquid and boiling heat transfer coefficients of  $240$  Btu/hr-ft<sup>2</sup>-°R is required to obtain the overall oxygen circuit heat transfer coefficient of  $167$  Btu/hr-ft<sup>2</sup>-°R that would result in 95% exit quality. The major portion of the third stage has a relatively low temperature difference and moderate heat flux and considering the statements above concerning the high density fin a minimum of film boiling will take place. Thus, an overall oxygen heat transfer coefficient greater than  $167$  Btu/hr-ft<sup>2</sup>-°R appears to be realistically achievable.

### PRESSURE AND TEMPERATURE MAP

Figures B-6 and B-7 show the temperature and pressure map for the hydrogen circuit and oxygen circuit, respectively. The temperatures shown are estimated. The flow pattern (thus, the temperature pattern) in a three-pass cross-counterflow arrangement with mixed flow in the oxygen circuit, the third stage of the hydrogen circuit and in the mitered turns is very complex.

UA538949-1  
OXYGEN/GASEOUS HYDROGEN HEAT EXCHANGER  
Intersection of Oxygen and Hydrogen  
Manifold With Core Geometry



FD 320488  
862210  
0800B

FIGURE B-1

UA538949-1  
OXYGEN/GASEOUS HYDROGEN HEAT EXCHANGER

Heat Transfer Model for  
Hydrogen/Resistance Layer Nosepiece

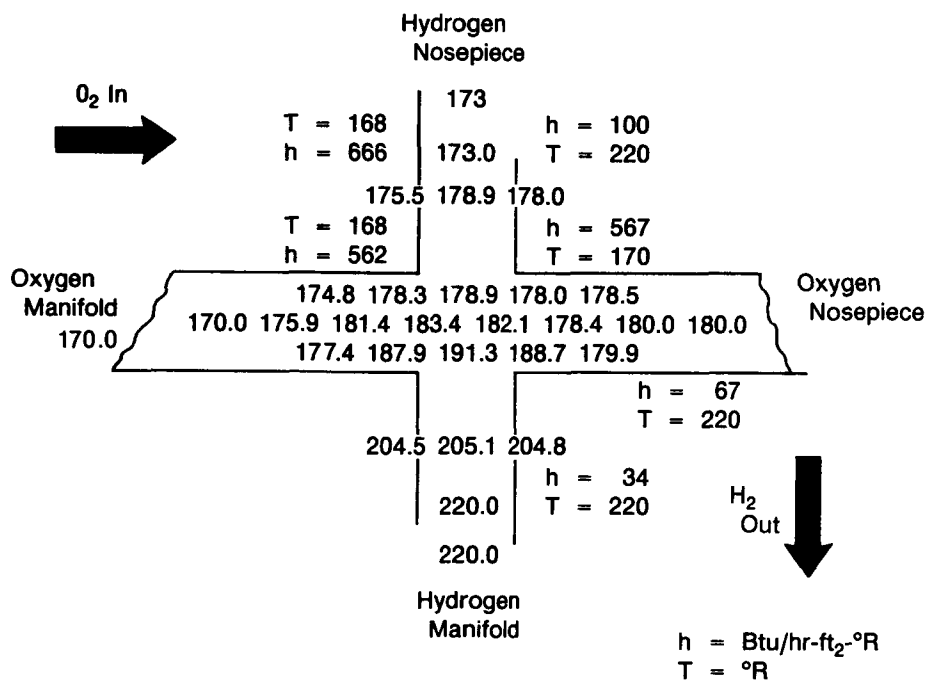
$T = 168^{\circ}\text{R}$   
 $\bar{h} = 612 \text{ Btu/hr-ft}^2\text{-}^{\circ}\text{R}$

Oxygen  
 $T = 168^{\circ}\text{R}$   
 $\bar{h} = 484$   
 $\text{Btu/hr-ft}^2\text{-}^{\circ}\text{R}$

172.3	172.5	172.6	RESISTANCE LAYER
172.5	172.7	173.0	
172.5	172.9	173.4	<p>Hydrogen <math>\bar{h} = 100 \text{ Btu/hr-ft}^2\text{-}^{\circ}\text{R}</math> <math>T_h = 257^{\circ}\text{R}</math></p> <p>- SYM</p>
			RESISTANCE LAYER

FIGURE B-2

UA538949-1  
**OXYGEN/GASEOUS HYDROGEN HEAT EXCHANGER**  
Heat Transfer Model for Manifold Analysis



FD 320489  
862210  
0800B

FIGURE B-3

UA538949-1  
OXYGEN/GASEOUS HYDROGEN HEAT EXCHANGER

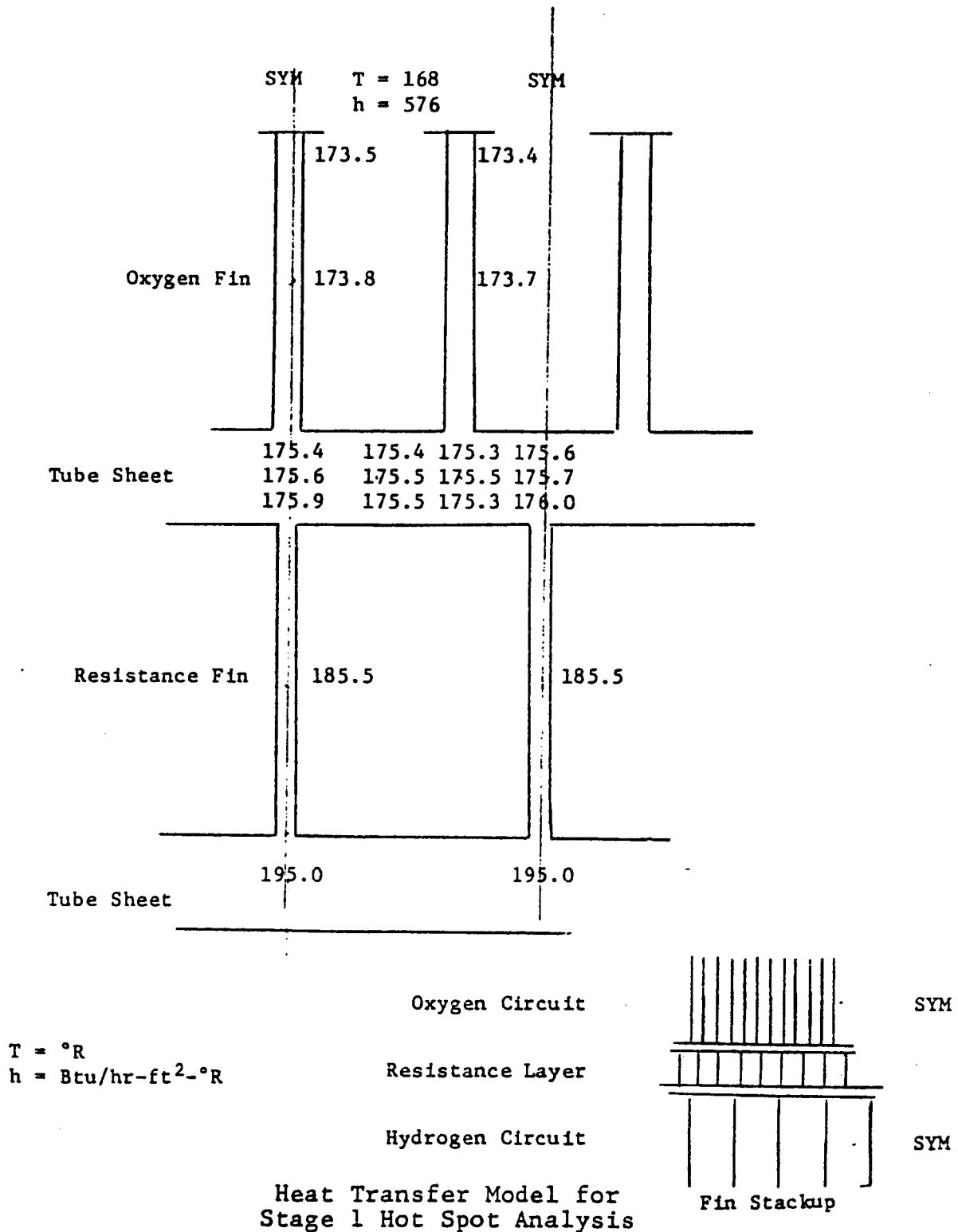


FIGURE B-4

UA538949-1  
OXYGEN/GASEOUS HYDROGEN HEAT EXCHANGER  
Schematic of Oxygen Circuit Fin

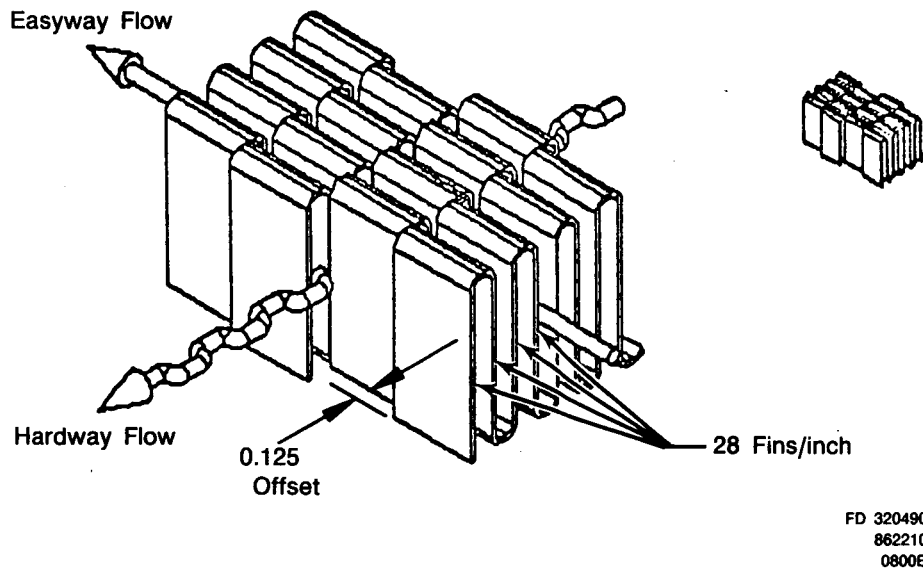


FIGURE B-5



W = 11.4 lbs/min  
P = 46.7 psia  
T = 659°R

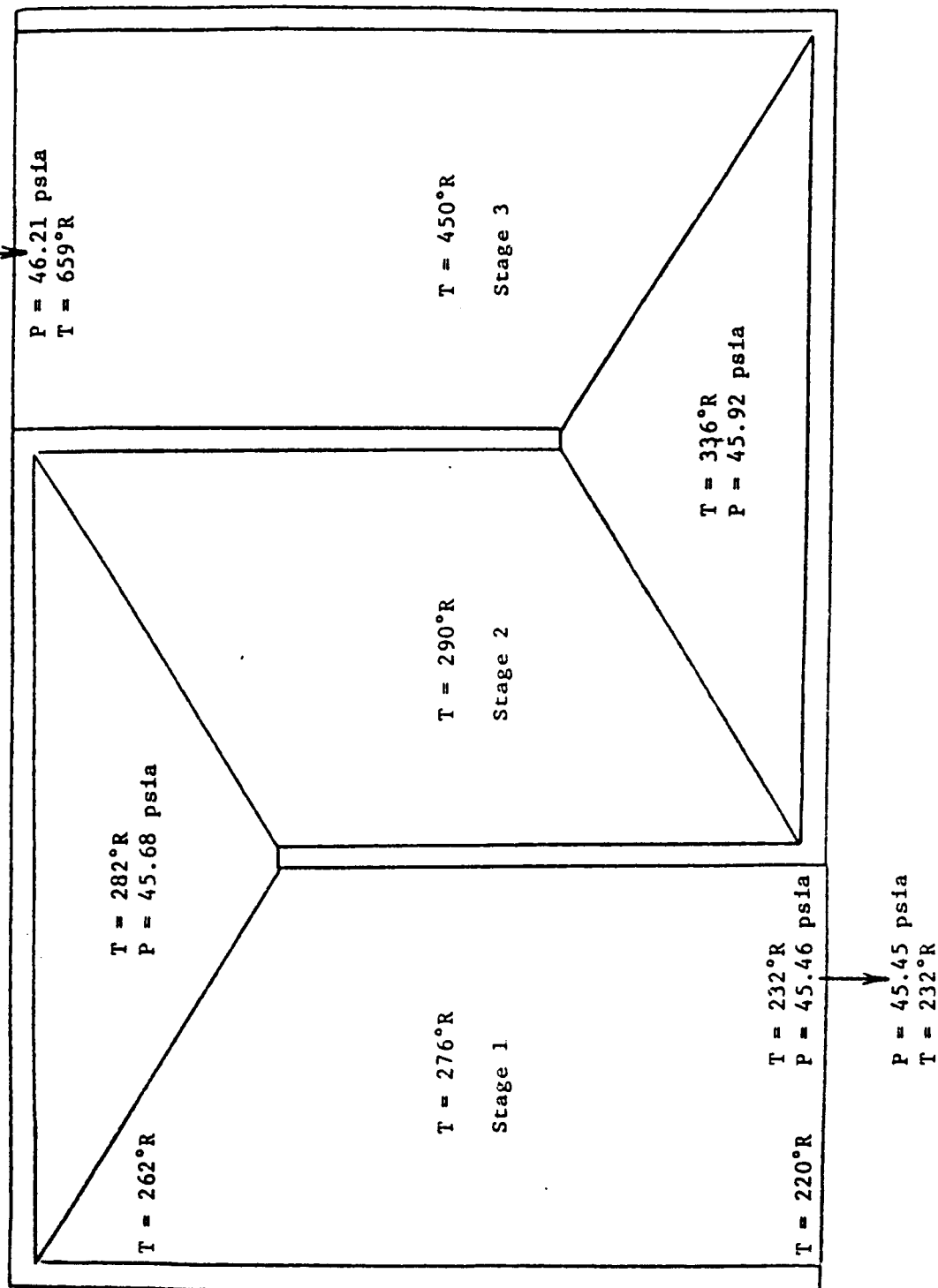
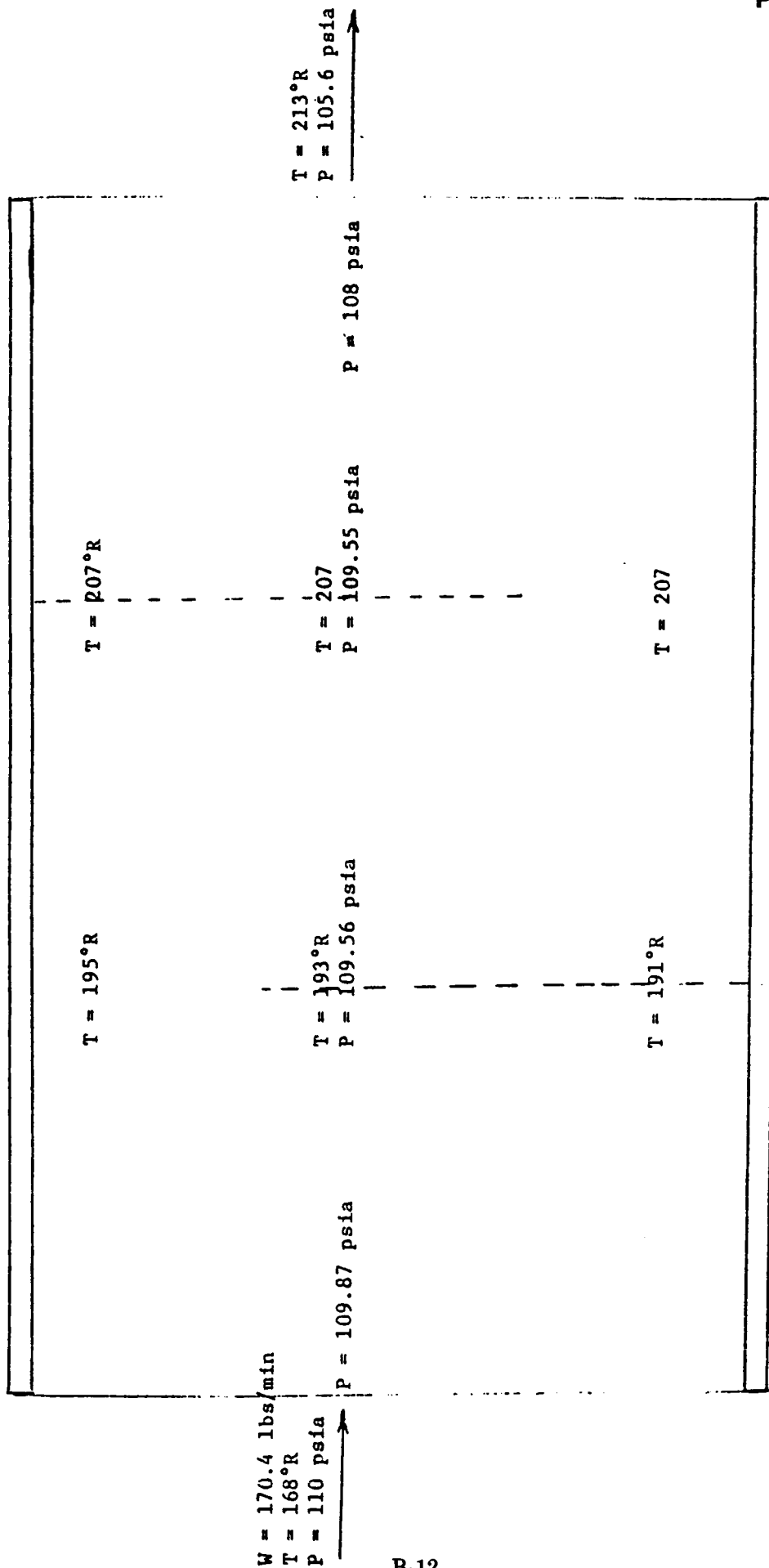


FIGURE B-6

Estimated Pressure/Temperature Map for Hydrogen Circuit

UA538949-1  
OXYGEN/GASEOUS HYDROGEN HEAT EXCHANGER

Estimated Pressure/Temperature Map for Oxygen Circuit



B-12

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FIGURE B-7

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16. Abstract  The RL10-IIB engine, a derivative of the RL10, is capable of multi-mode thrust operation. This engine operates at two low thrust levels: tank head idle (THI), which is approximately 1 to 2 percent of full thrust, and pumped idle (PI), which is 10 percent of full thrust. Operation at THI provides vehicle propellant settling thrust and efficient engine thermal conditioning; PI operation provides vehicle tank pre-pressurization and maneuver thrust for low-g deployment.  Stable combustion of the RL10-IIB engine at THI and PI thrust levels can be accomplished by providing gaseous oxygen at the propellant injector. Using gaseous hydrogen from the thrust chamber jacket as an energy source, a heat exchanger can be used to vaporize liquid oxygen without creating flow instability.  This report summarizes the design and analysis of a United Aircraft Products (UAP) low-rate heat transfer heat exchanger concept for the RL10-IIB rocket engine. The design represents a second iteration of the RL10-IIB heat exchanger investigation program. The design and analysis of the first heat exchanger effort is presented in more detail in NASA CR-174857. Testing of the previous design is detailed in NASA CR 179487					
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